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by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

DEPARTMENT OF ELECTRICAL ENGINEERING

EDMONTON, ALBERTA

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UNIVERSITY OF ALBERTA

RIVER MODEL PROFILE MEASURING SYSTEM

by

Neal Allan Patterson

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The undersigned certify that they have read and recommended to the Faculty of Graduate Studies for acceptance, a thesis entitled RIVER MODEL PROFILE MEASURING SYSTEM submitted by Neal Allan Patterson in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

This thesis describes the design, development, and final construction of an instrument to plot automatically the bottom and water surface profiles of river models.

A controlled light source and a light sensor mounted in a slender probe are used in a novel optical arrangement to sense surface proximity. The probe positioning mechanism is electromechanical and uses tachometer feedback for stability.

The instrument is remotely controlled and the system outputs are used to drive an X-Y plotter.

Solid state circuitry is used throughout.

ACKNOWLEDGEMENTS

The author wishes to thank the staff and graduate students of the Departement of Electrical Engineering for their helpfulness during the preparation of this thesis.

Particular appreciation is expressed to Professor Y.J.Kingma for his supervision and encouragement, and to my wife Weslie for her help and understanding.

The. financial assistance provided by the University of Alberta is gratefully acknowledged.

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CHAPTER ONE

INTRODUCTION

1.1 PROBLEM OUTLINE

In the hydrology field of Civil Engineering, considerable use is made of scale models of rivers and harbours. These are used to determine the effect of structures in the path of flow, to study erosion and similar problems.

In these studies, it is often desireable to measure the profile of both the bed of the model and the surface of the water. It should be noted that these are two different measurements and they should be able to be taken both quickly and accurately. It is also desireable that taking these measurements should not disturb the model due to turbulence or scouring.

The instruments in common use today for measuring the surface of the water in models normally use a sharply pointed probe attached to a calibrated device. A point on the surface is obtained when the tip of the probe just touches the water.

Instruments for measuring the bed of the model accurately are not pleantiful. One particular instrument uses a resistance bridge method, and another employs an acoustical method, but both of these instruments have operating limitations.

It should also be mentioned that visual observations can be taken for both cases, particularly when a model is constructed with one transparent vertical side. This method is not always convenient and often lacks accuracy.

There is a demonstrated need for an instrument which will give a continous profile of either the water surface or the bed of the model, quickly, accurately, and with a minimum of effort.

This thesis describes the design , construction, and performance of such an instrument which is referred to in following chapters as the River Plotter for lack of a more precise name.

1.2 PERFORMANCE REQUIREMENTS

The River Plotter was primarily intended to plot the profiles of the beds of river models, but it was also hoped that the water surface profile could also be plotted with minor adjustements.

The River Plotter requirements were:

a) A continous profile along a preset straight line

b) A resolution of ± 1/32 inch or better

c) A dynamic response sufficiently fast to ensure a reasonable traversing speed along a profile

d) A probe small enough not to cause turbulence or scouring

e) A minimum of external controls

f) Only 60 Hz. A.C. power required for operation

1.3 PRINCIPLES AND METHOD OF OPERATION

Figurel.1 shows the arrangement used for sensing proximity to the surface to be measured. To the best of the author's knowledge, this arrangement and application of the light sensor is original.

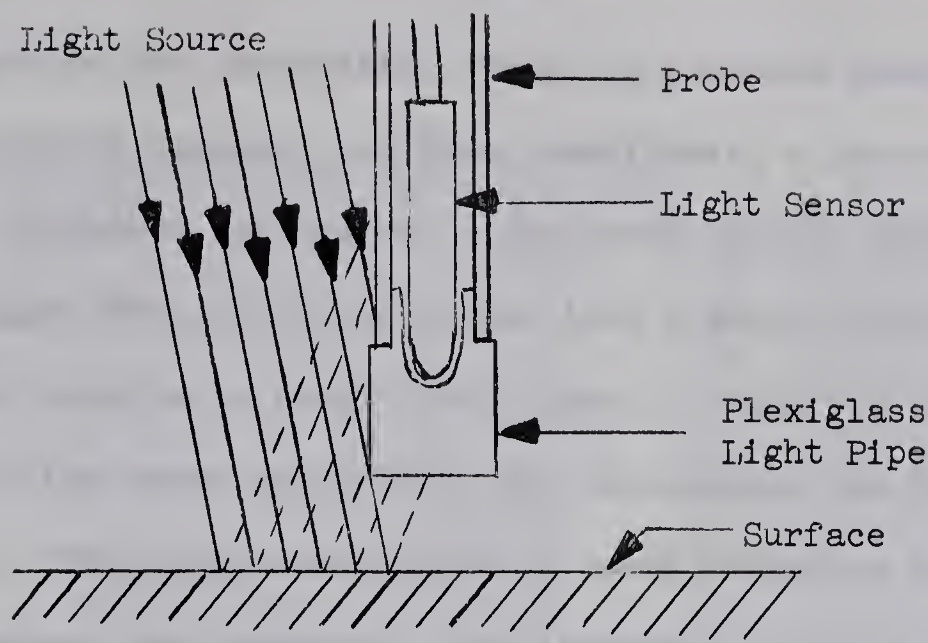

FIGURE 1.1 SURFACE PROXIMITY LIGHT SENSOR ARRANGEMENT

The principle is that a light source illuminates the surface at a desired intensity. The light is reflected back from the surface and enters the light sensor. The light sensor produces a signal proportional to the amount of light entering through the lens. The probe is operated close to the surface, so that the probe itself blocks some of the light producing a shadow on the surface. When the sensor is on the surface itself, this corresponds to the lowest light intensity (maximum shadow), and at a distance above the surface, there will be a point of maximum light intensity (no shadow). An operating point is picked between these two conditions and the signal from the light sensor is used to maintain the probe position at this distance above the surface. This distance remains the same for a constant light intensity and by setting the X-Y recorder to compensate for this distance, an accurate profile of the actual surface is plotted.

The system for controlling the probe position consists of an unusual motor control circuit, two power amplifiers, a servo motor and a gear and leadscrew arrangement. The motor control circuit converts the signal from the light sensor into a motor control field signal, and also supplies a fixed field signal. These two signals are amplified by the two power amplifiers, and the outputs are fed into the servo motor. The servo motor drives a speed reduction geartrain which in turn drives the leadscrew. The leadscrew converts the rotational motion of the servo motor and geartrain into linear motion. The probe is connected directly to the leadscrew and is thereby driven up and down to maintain the operating distance above the surface. The servo motor also has a tachometer output, and this signal is fed back into the motor control circuit to improve stability and damping.

A precision potentiometer is connected through a gear into the geartrain, and ± 15 volts are applied across the upper and lower terminals. The wiper of the potentiometer produces a voltage which varies linearly with the probe position. This signal is applied to a high input impedance, low output impedance device, and this output voltage is then used as the vertical or Y signal to drive an X-Y recorder.

The probe, motor control circuit, amplifiers, servo motor, precision potentiometer, and other equipment are mounted on a trolley which can be towed back and forth on a set of rails as shown in Figure 1.2. A second motor is used to tow the trolley and the towing cable passes around a pulley on the trolley. This pulley is attached to a set of gears which drive a second precision potentiometer. This

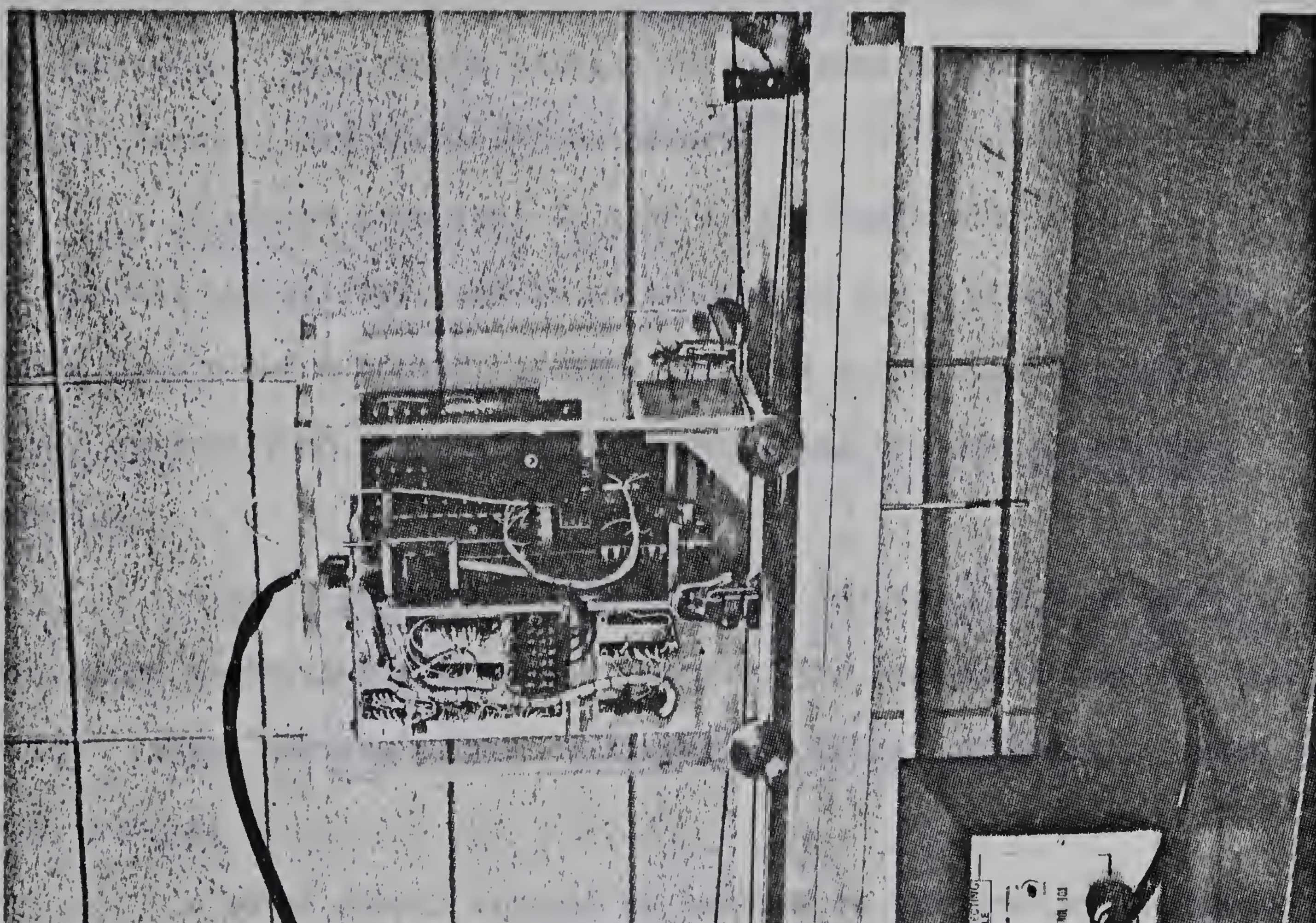

FIGURE 1.2 THE RIVER PLOTTER

potentiometer produces a voltage through another impedance changing device which is proportional to the horizontal position of the trolley on the rails. This output voltage is then used as the horizontal or the X signal to drive the X-Y recorder.

A sealed beam lamp is used as the light source to illuminate the surface, and it is mounted on the trolley. A second light sensor and a control circuit are used to maintain a constant light intensity on the surface by controlling the current through the lamp.

A multi-conductor cable connects the trolley to a control box which contains the external controls, the horizontal and vertical output signal terminals, and equipment too bulky and heavy to mount on the trolley.

A power supply circuit is mounted on the trolley to supply $\pm$ 15 volts D.C. to the other circuits, which are all solid state.

To summarize, the River Plotter is a new and original instrument, developed around a novel application of a light sensor for positional control. The servo motor control circuit uses an unusual arrangement of multivibrators to obtain phase shift between fixed and control field signals.

CHAPTER TWO

LIGHT SENSORS AND PROBE CONSTRUCTION

2.1 THE SURFACE PROXIMITY SENSOR

The heart of the system is the device which senses proximity to the surface to be measured. The River Plotter uses a TEXAS INSTRUMENTS LS - 400 optoelectronic device or light sensor mounted at the end of a probe. Using the signal from the light sensor, the probe is electromechanically controlled to follow very slightly above the surface to be measured.

Figure 2.1(a) shows the symbol used for the light sensor, the biasing arrangement, and the output signal point.

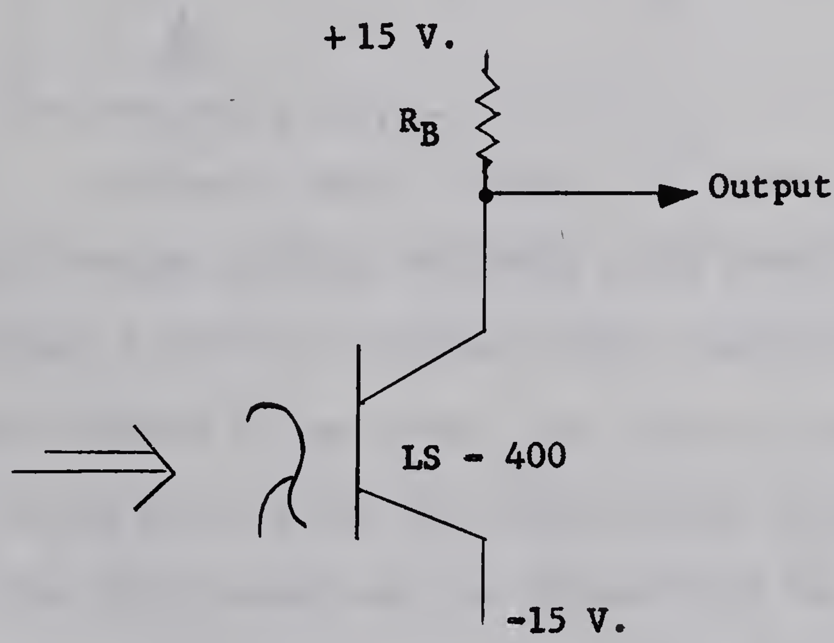

FIGURE 2.1(a) LIGHT SENSOR BIASING

The light sensor can be thought of as a transistor which derives base bias from the light energy it absorbs through the lens. The larger the amount of light entering the lens, the higher the

collector current is,and conversely. The light sensor is quite sensitive over a wide range of light intensities and this permits flexibility in applications. The resistor R_B serves to limit the collector current at high light intensities and to set the D.C. output level for a desired light intensity.

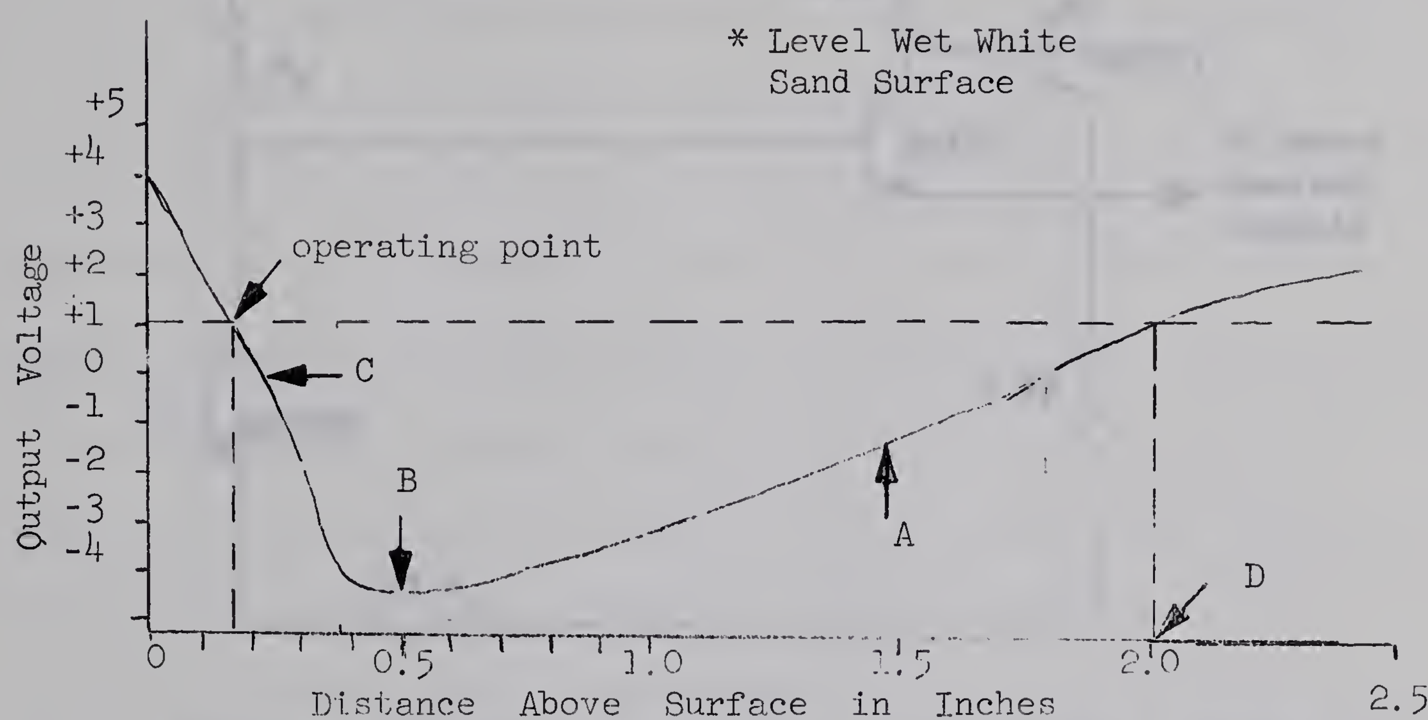

FIGURE 2.1(B) TYPICAL SURFACE PROXIMITY LIGHT SENSOR CHARACTERISTICS

Figure 2.1(b) is a typical output characteristic of the light sensor mounted in the probe. The shape of the characteristic especially around point B can vary considerably depending on the biasing of the light sensor and the intensity of the light source.

The motor control circuit is designed to drive the probe downward for a negative light source signal and upward for a positive signal. The system is therefore a closed loop and tends to maintain the probe at a fixed distance from the surface corresponding to the operating point shown on part C of the characteristic.

In order for the system to be self-starting or to find the operating point automatically, the system must start from a

point on the characteristic no further above the surface than point D . Normally the system does operate inside point D, but the system can be remotely controlled to run the probe up or down to start the system operating automatically.

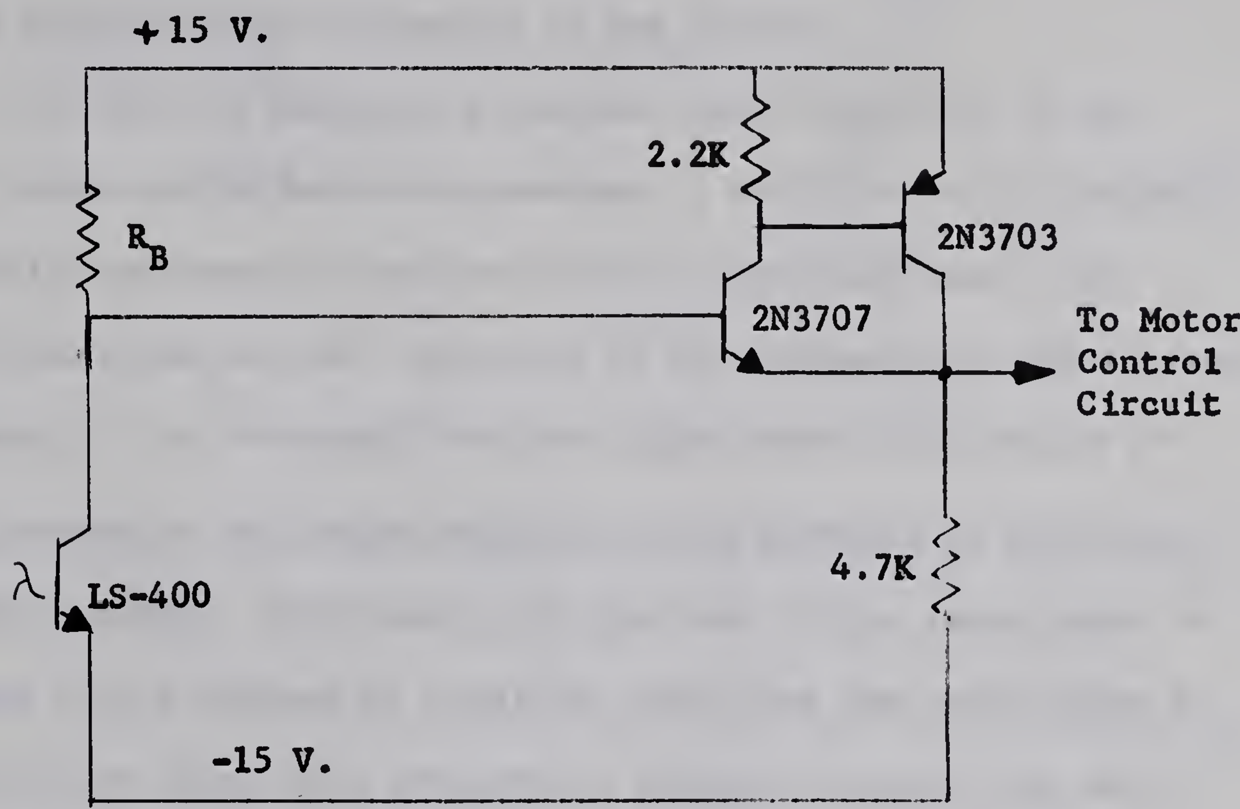

FIGURE 2.2 SURFACE PROXIMITY LIGHT SENSOR CIRCUIT

Figure 2.2 shows the light sensor circuit used to control the position of the probe.

The compound transistor emitter follower circuit has an input impedance in the order of 10M ohms and therefore does not load the light sensor which has an impedance equal to R_B at the operating point.

2.2 THE SENSOR FOR CONTROLLING THE LIGHT SOURCE

The light intensity on a surface varies inversely with the distance of the surface from the source. The light source is mounted directly on the trolley and since the distance to the surface varies, it is necessary to control the intensity of the source to provide a constant light intensity on the surface.

In order to maintain a constant light intensity on the surface, some sensing device is necessary , and in order to control the intensity accurately, the lens of the sensor used must look upward at the light source. An error in the intensity on the surface proportional to the distance from the light source will result if this distance is not large compared to the distance of the lens from the surface. This means that the lens of the sensor must be as close to the surface as possible, and since the sensor used is over 1/2 inch long, this presented a physical problem that was overcome by using a light pipe attached to the probe as shown in Figure 2.3.

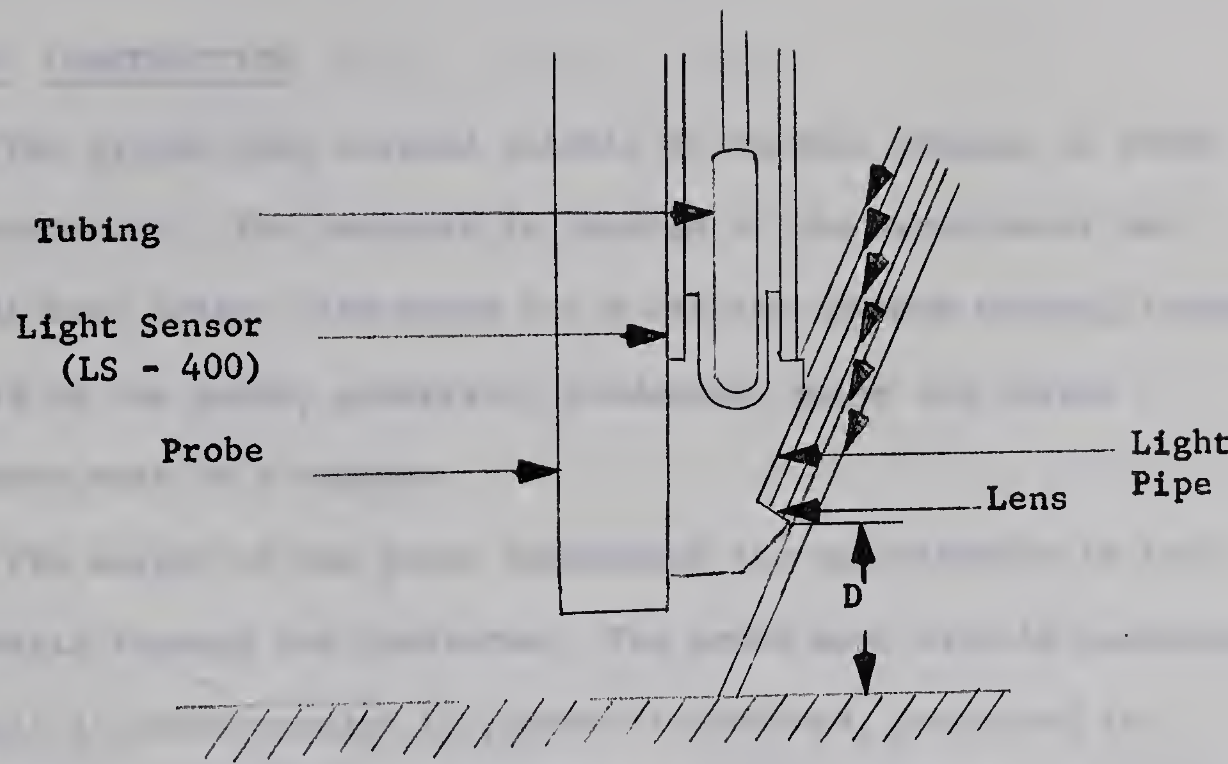

FIGURE 2.3 LIGHT SENSOR ARRANGEMENT FOR CONTROLLING THE LIGHT SOURCE

The light pipe is a plexiglass rod, ground as shown in Figure 2.3, painted with white paint for good internal reflection, and then with dense black paint to keep out unwanted light and not cause unwanted external reflections. The light pipe is designed to concentrate the light entering the lens on to the bottom of the pipe, where it is reflected back up to the light sensor. Using the same biasing arrangement as shown in Figure 2.1(a), the light sensor output signal is used to control the light source. The distance "D" shown in Figure 2.3 is small enough that the error in surface light intensity, as the distance from the source varies, is acceptable.

The light sensor circuit used to control the light source intensity is identical to that shown in Figure 2.2, except that R_B is 6.8M ohms for this circuit, and the output connects to the light source control circuit.

2.3 PROBE CONSTRUCTION

The system must respond quickly to surface changes in order to plot accurately. The response is limited by the servo motor and the load it must drive. The motor has a certain maximum torque, therefore the inertia of the motor, geartrain, leadscrew, probe and output potentiometer must be a minimum.

The weight of the probe determines its contribution to the system inertia through the leadscrew. The probe must also be mechanically rigid, small in cross-section to prevent turbulence, resistant to corrosion in water and air, and hollow to accomodate the leads from the light sensors. A 3/16 inch outside diameter thinwall brass tube is used for the probe with the light sensors mounted as shown in Figure 2.4.

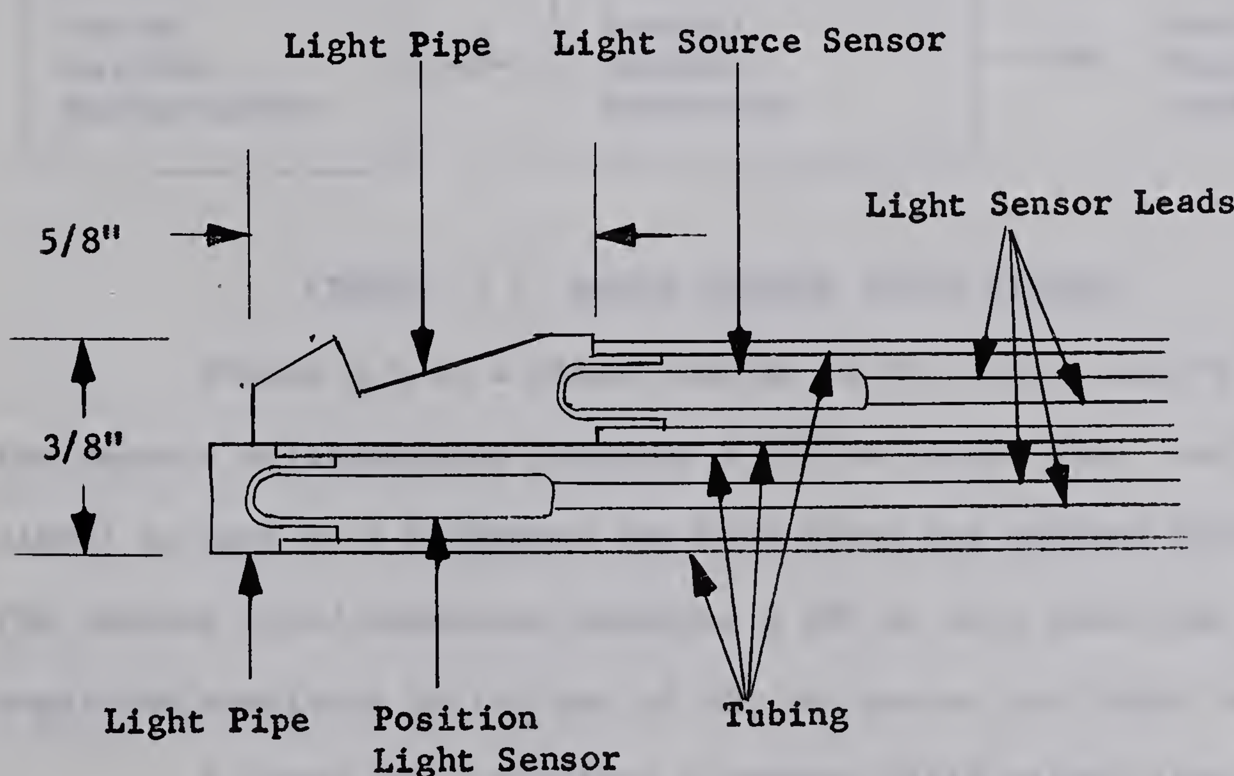

FIGURE 2.4 PROBE CONSTRUCTION

CHAPTER THREE

MOTOR CONTROL CIRCUIT

3.1 GENERAL DESCRIPTION

A 400 Hz servo motor was chosen to drive the probe instead of a 60 Hz motor for faster system response, less weight, smaller size, and to avoid 60 Hz pickup. The servo motor therefore requires 400 Hz fixed and control field signals. The motor control circuit produces the low level fixed field and control field 400 Hz signals which are then amplified by two power amplifiers and fed into the motor fields.

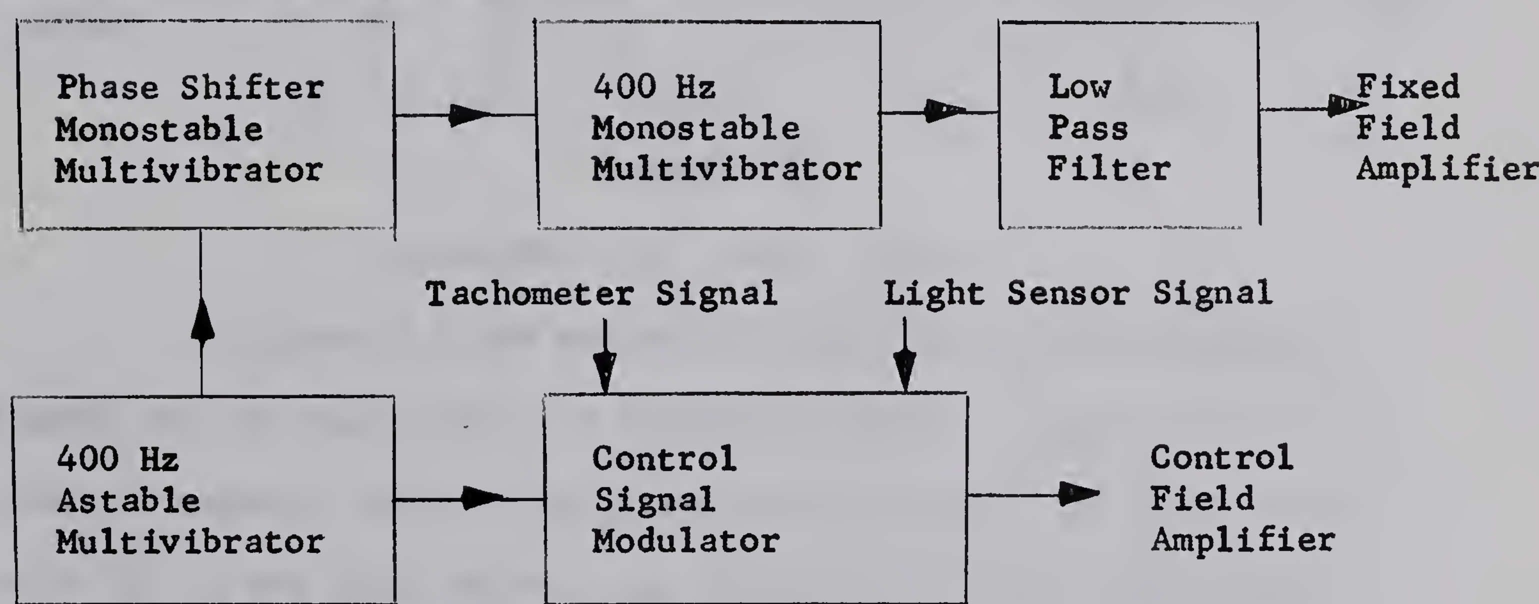

FIGURE 3.1 MOTOR CONTROL BLOCK DIAGRAM

Figure 3.1 is a block diagram of the motor control circuit. The astable multivibrator produces a 400 Hz square wave, and this signal is used as a reference for both fixed and control field signals. The control field modulator produces a 400 Hz sine wave that is amplitude modulated by the sum of the tachometer and light sensor signals.

A servo motor requires a control field signal that is 90 degrees out of phase with the fixed field in order to develop maximum torque.

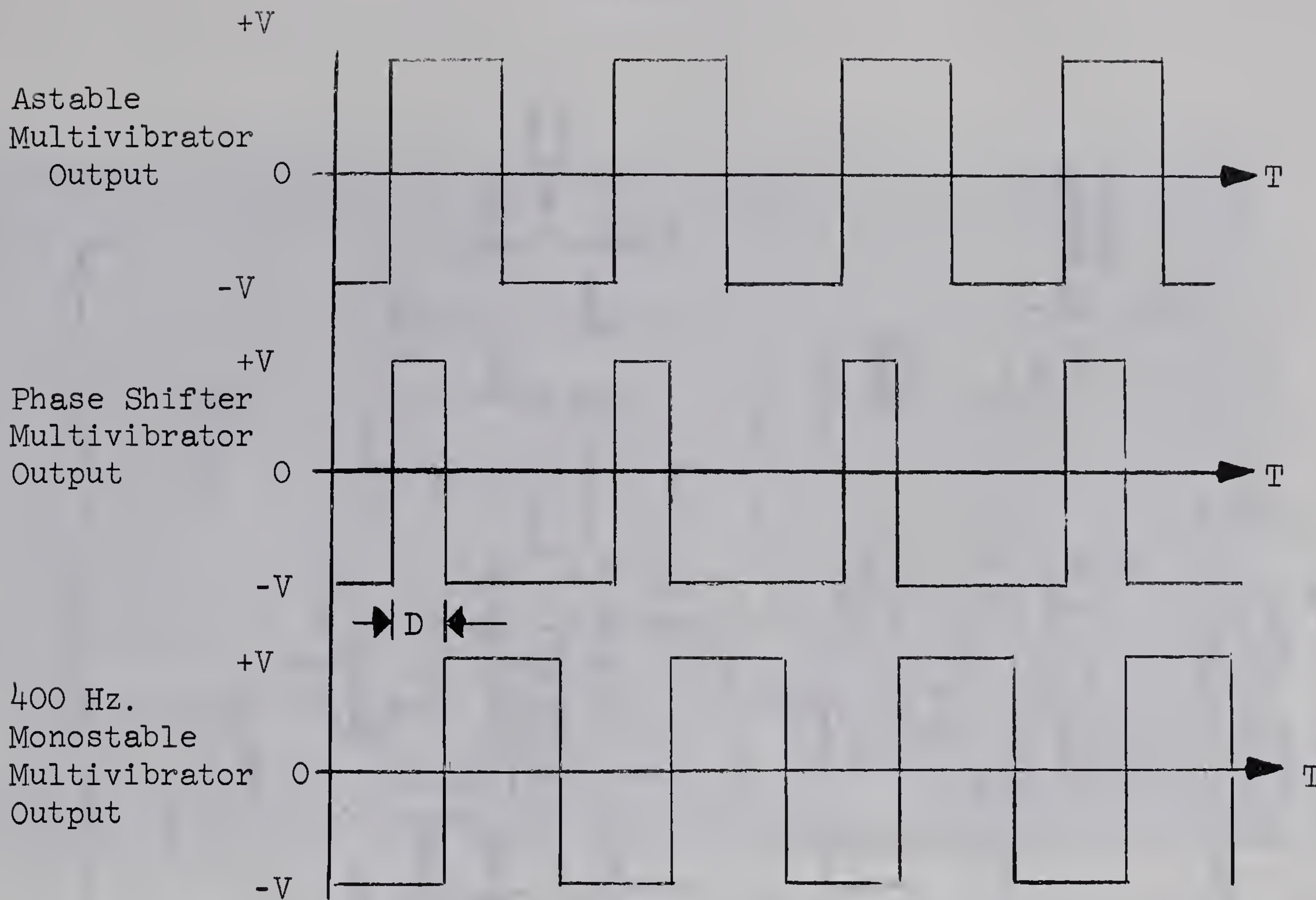

FIGURE 3.2

DERIVATION OF FIXED FIELD

In Figure 3.2 the method of obtaining a 400 Hz. signal 90 degrees out of phase with the reference signal is shown. This is a novel arrangement which is quite versatile, since the width of the pulse "D" in the phase shifter can be adjusted over a wide range in order to compensate for differences in phase shift in subsequent circuits. The low pass filter attenuates the 400 Hz. harmonics in the square wave, so that the output of the low pass filter is a constant amplitude 400 Hz. sine wave.

Figure 3.3 shows the complete motor control circuit. Figure 3.4(a) shows the front of the motor control printed circuit board, and Figure 3.4(B) shows the layout of the back of the board.

3.2 THE MULTIVIBRATORS

In Figure 3.3, the astable multivibrator has diodes D1 and

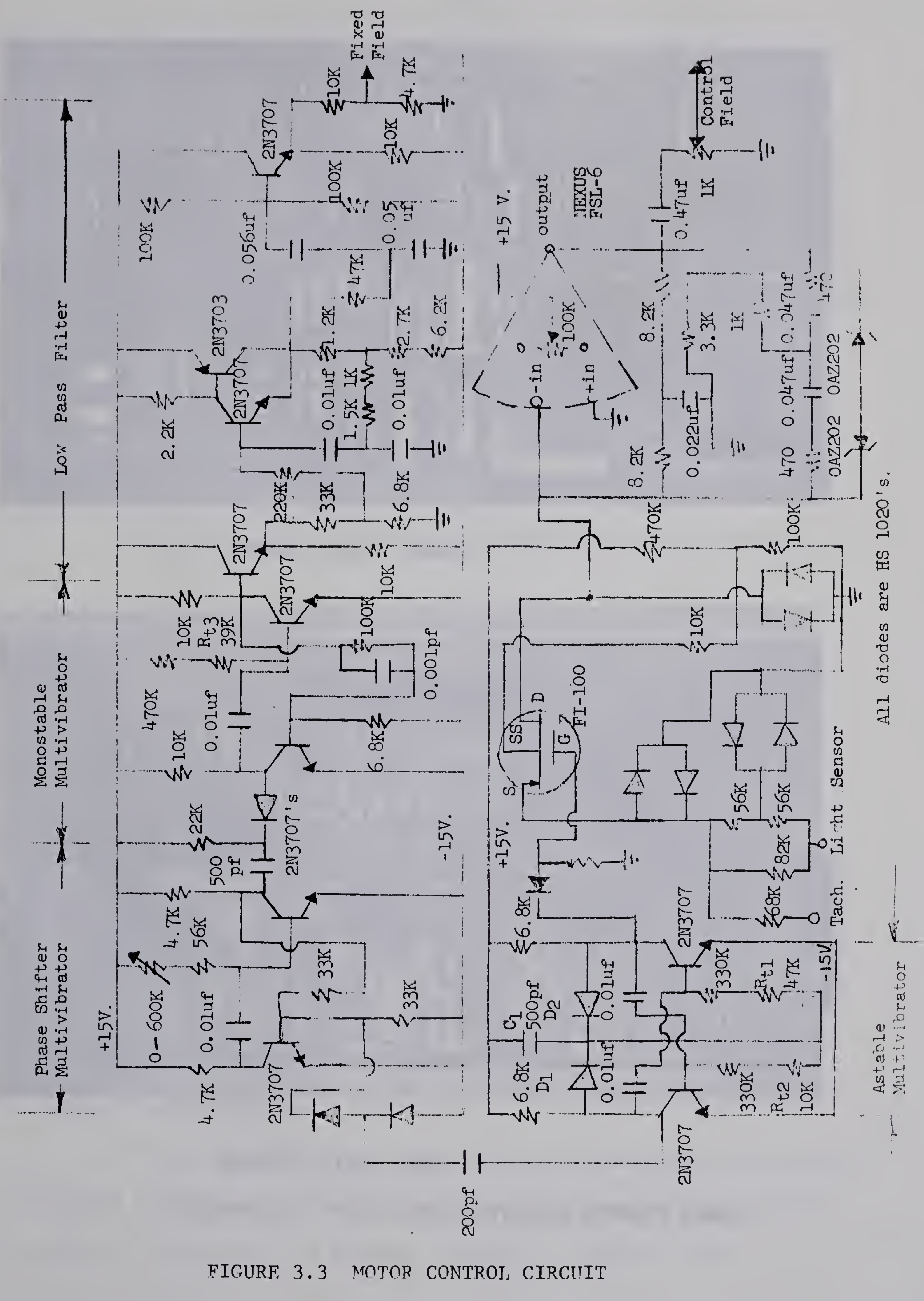

FIGURE 3.3 MOTOR CONTROL CIRCUIT

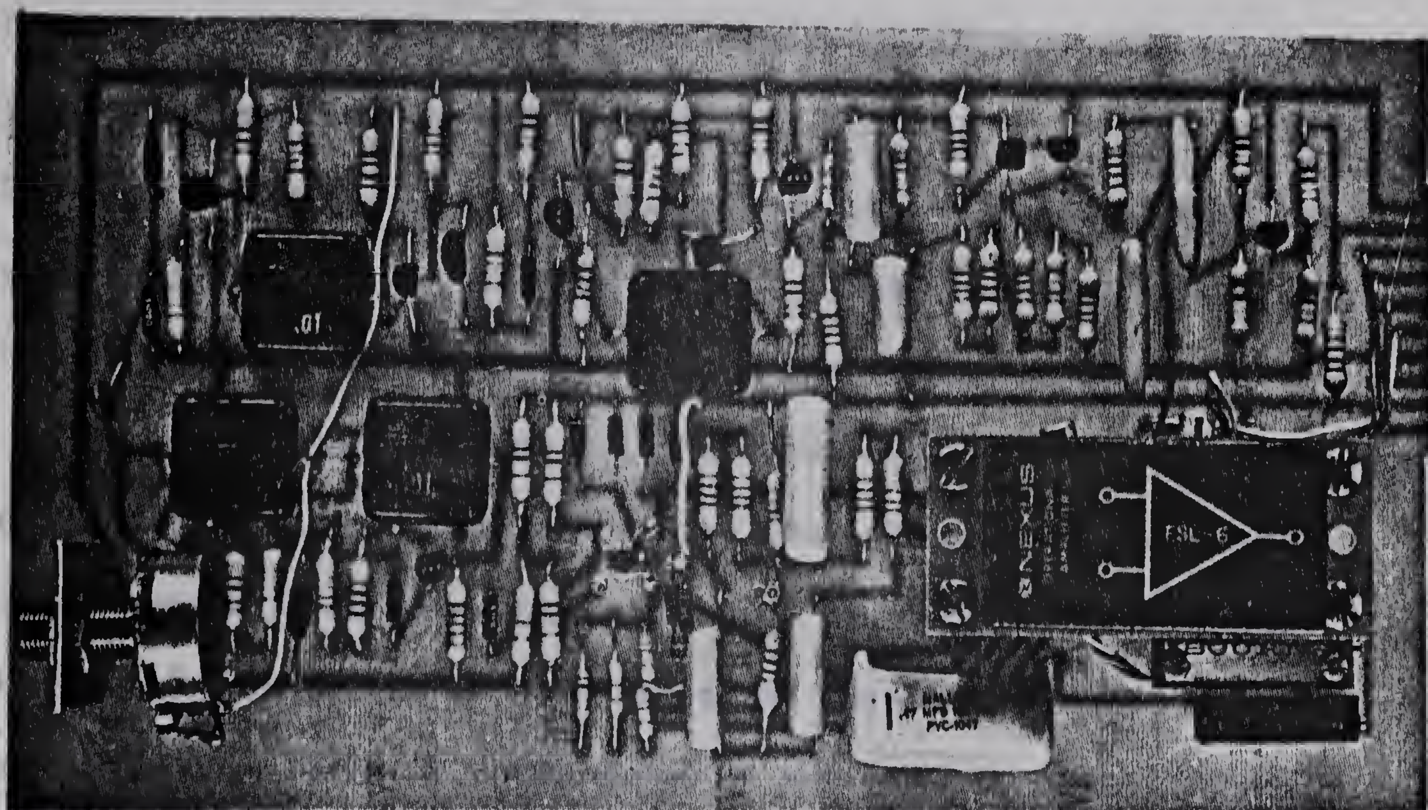

FIGURE 3.4(a) FRONT

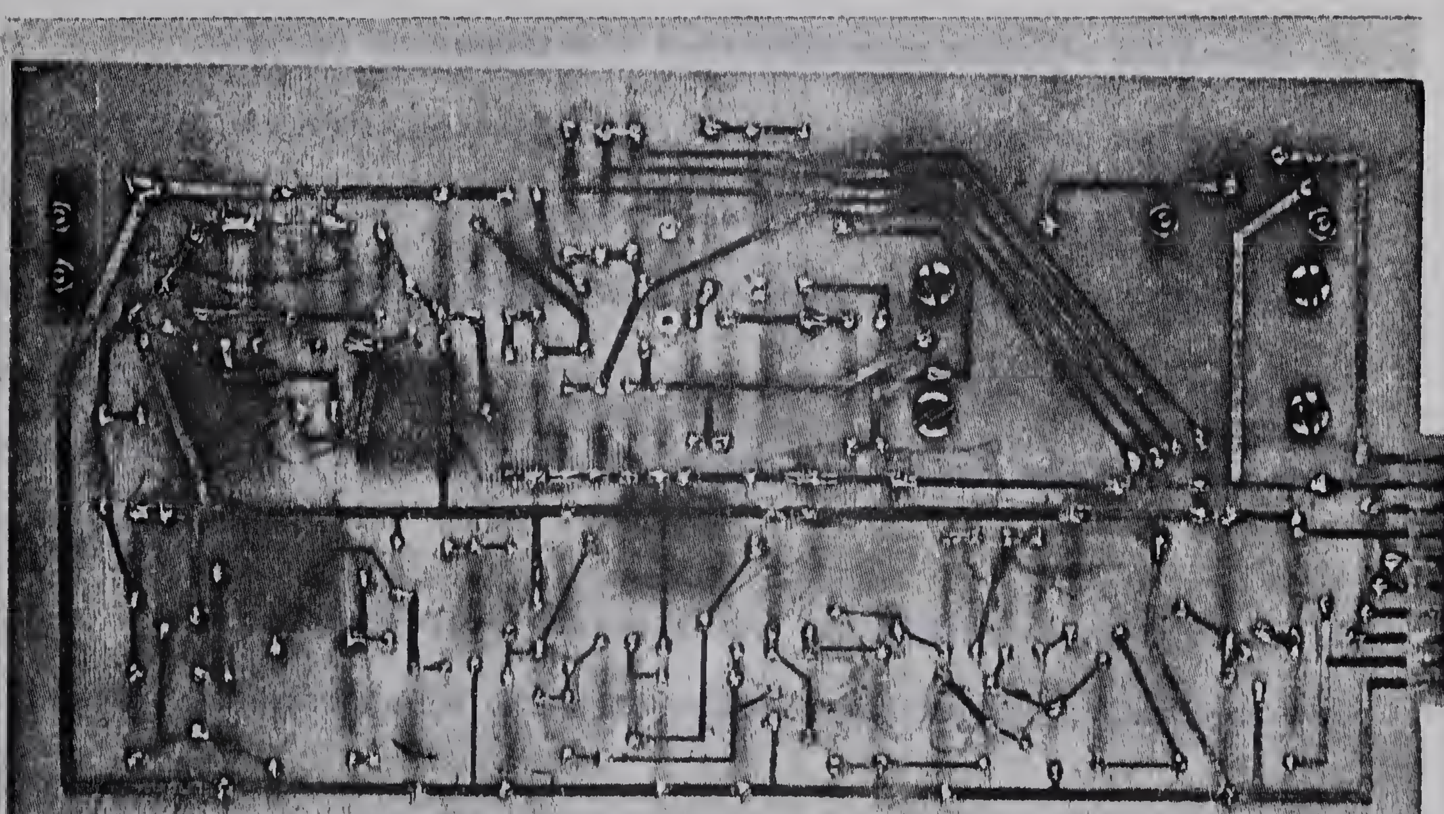

FIGURE 3.4(b) BACK

FIGURE 3.4 MOTOR CONTROL PRINTED CIRCUIT BOARD

D2 and capacitor C1 to ensure that the multivibrator will start switching immediately when the power is turned on. Resistors R_{T1} and R_{T2} are chosen by trial and error to adjust the pulse widths for a symmetrical 400 Hz square wave output. These resistors are necessary due to slight differences in value of the timing capacitors.

The phase shifter multivibrator employs base triggering through the capacitor diode arrangement from the collector of the astable multivibrator. As shown in Figure 3.2, the output of the phase shifter switches from -V to +V when the astable multivibrator output switches from -V to +V. The width of the phase shifter +V output pulse is adjusted with the 600K ohm potentiometer for maximum motor torque.

The 400 Hz monostable multivibrator employs collector triggering through the capacitor, resistor, and diode network from the output collector of the phase shifter. The output of this multivibrator switches from -V to +V when the output of the phase shifter switches from +V to -V. The trim resistor R_{T3} is used to obtain a symmetrical square wave output as in the case of the astable multivibrator.

Mica capacitors are used for the timing capacitors in the three multivibrators in order to reduce temperature effects on the frequency.

3.3 THE LOW PASS FILTER

In Figure 3.3, the output of the 400 Hz monostable multivibrator is connected through an emitter follower to a resistor voltage divider. The output of the divider is connected through a 220K ohm input

resistor to a bootstrapped transistor compound. This circuit is a second order active low pass filter and the resistor and capacitor network on the output provide an additional first order low pass filter, so that the combined effect is that of a third order low pass filter. The output of the filter is fed into an impedance matching circuit, and the output from this circuit is fed into a resistor voltage divider which serves as the gain control for the fixed field amplifier.

3.4 THE MODULATOR

The modulator sums the low frequency light sensor and tachometer signals and produces a 400 Hz. sine wave which is amplitude modulated by the sum of the input signals.

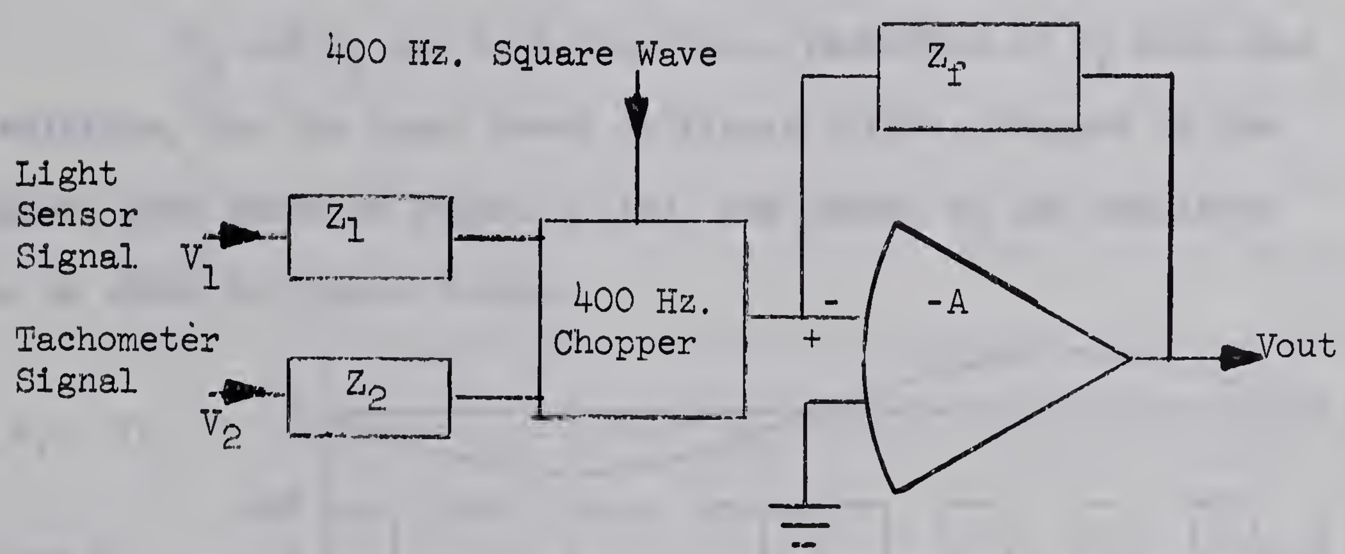

FIGURE 3.5 BLOCK DIAGRAM OF THE MODULATOR

Figure 3.5 shows a block diagram of the modulator. A chopper is a device which acts as a switch which is opened and closed

at a frequency corresponding to the frequency of the controlling signal. This corresponds to a device which changes from a very low impedance to a very high impedance to either pass or block current. The control signal in Figure 3.5 is a 400 Hz square wave; the chopper passes current for the -V control signal and blocks current for the +V control signal. Therefore if the input impedance of the chopper is Z_c, then according to feedback control theory:

$$V_{out} = -Z_f \left[\frac{V1}{Z_1 + Z_c} + \frac{V2}{Z_2 - Z_c} \right] .$$

Therefore if $Z_c \gg Z_1$, Z_2 and Z_f,

then $V_{out} \cong 0$.

If $Z_c \ll Z_1$, Z_2 and Z_f,

then $V_{out} \cong -Z_f \left[\frac{V_1}{Z_1} + \frac{V_2}{Z_2} \right]$.

Z_1 and Z_2 are both resistive, therefore if Z_f were also resistive, for the input shown in Figure 3.6(a), chopped by the square wave shown in Figure 3.6(b), the output of the modulator is as shown in Figure 3.6(c).

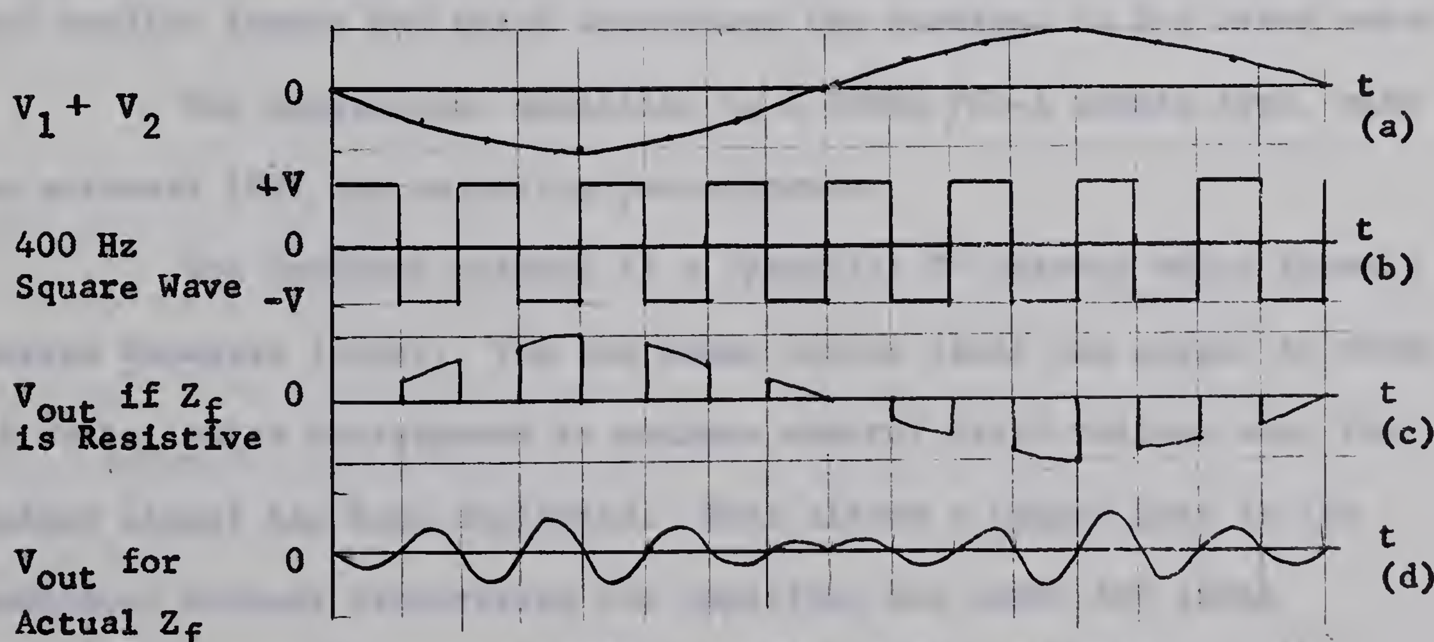

FIGURE 3.6 MODULATOR WAVEFORMS

This waveform is clearly not sinusoidal, therefore a feedback network Z_f with a narrow bandpass characteristic around 400 Hz is used and the output is as shown in Figure 3.6(d). This waveform is an amplitude modulated 400 Hz sine wave, and it is important to note that there is a 180 degree phase shift in the output signal when the input signal ($V_1 + V_2$) changes from positive to negative. This phase shift determines the direction of motor rotation and corresponds to changing the probe motion from upward to downward.

In Figure 3.3, the collector of the astable multivibrator is diode coupled to the gate of the Fl-100 MOSFET which acts as the chopper. The impedance form the source to drain changes from a very high impedance to a very low impedance when the gate voltage goes negative and vice versa when the gate voltage goes positive. The parallel diodes on the source and drain protect the MOSFET from voltage spikes.

The parallel diodes in the light sensor input network serve to make the input impedance 47K ohms for input voltages less than about $|1|$ volt, and 82K ohms for greater input voltages. This produces higher gain for smaller inputs and helps counteract the deadzone in the servo motor.

The operational amplifier is a NEXUS FSL-6 module type, with an external 100K ohm adjusting potentiometer.

The feedback network is a "parallel T" network which forms a narrow bandpass filter. The two Zener diodes limit the output to about ± 5 volts, which corresponds to maximum control field voltage when the output signal has been amplified. This allows a higher gain in the modulator without overdriving the amplifier and motor for large input signals. The output is fed into a high pass capacitor

resistor section for additional low frequency filtering. The 1K ohm potentiometer serves as a gain adjustement for the control field power amplifier.

CHAPTER FOUR

PROBE POSITIONING ASSEMBLY

4.1 POWER AMPLIFIERS

For maximum speed, the servo motor requires 400 Hz, 115 volts R.M.S. on both control and fixed fields. Two power amplifiers are therefore required for the River Plotter, one each to amplify the control field signal and the fixed field signal from the motor control circuit.

The amplifiers (ref. 1) are identical and the circuit is shown in Figure 4.1. The amplifier is a class B push-pull type that drives a centertapped load directly off the collectors of the output transistors. The amplifier has a fixed voltage gain of about 55 db. when driving the respective servo motor fields. Power for the amplifier is obtained from the full-wave rectifier diode bridge.

Figure 4.2(a) shows the front of the power amplifier printed circuit board and Figure 4.2(b) shows the layout of the back of the board.

The RCA 40328 output transistors are mounted on a separate external heatsink.

The fixed field of the servo motor is not centertapped, therefore a centertapped toroid transformer is used with 300 ohm current limiting resistors as shown in Figure 4.3.

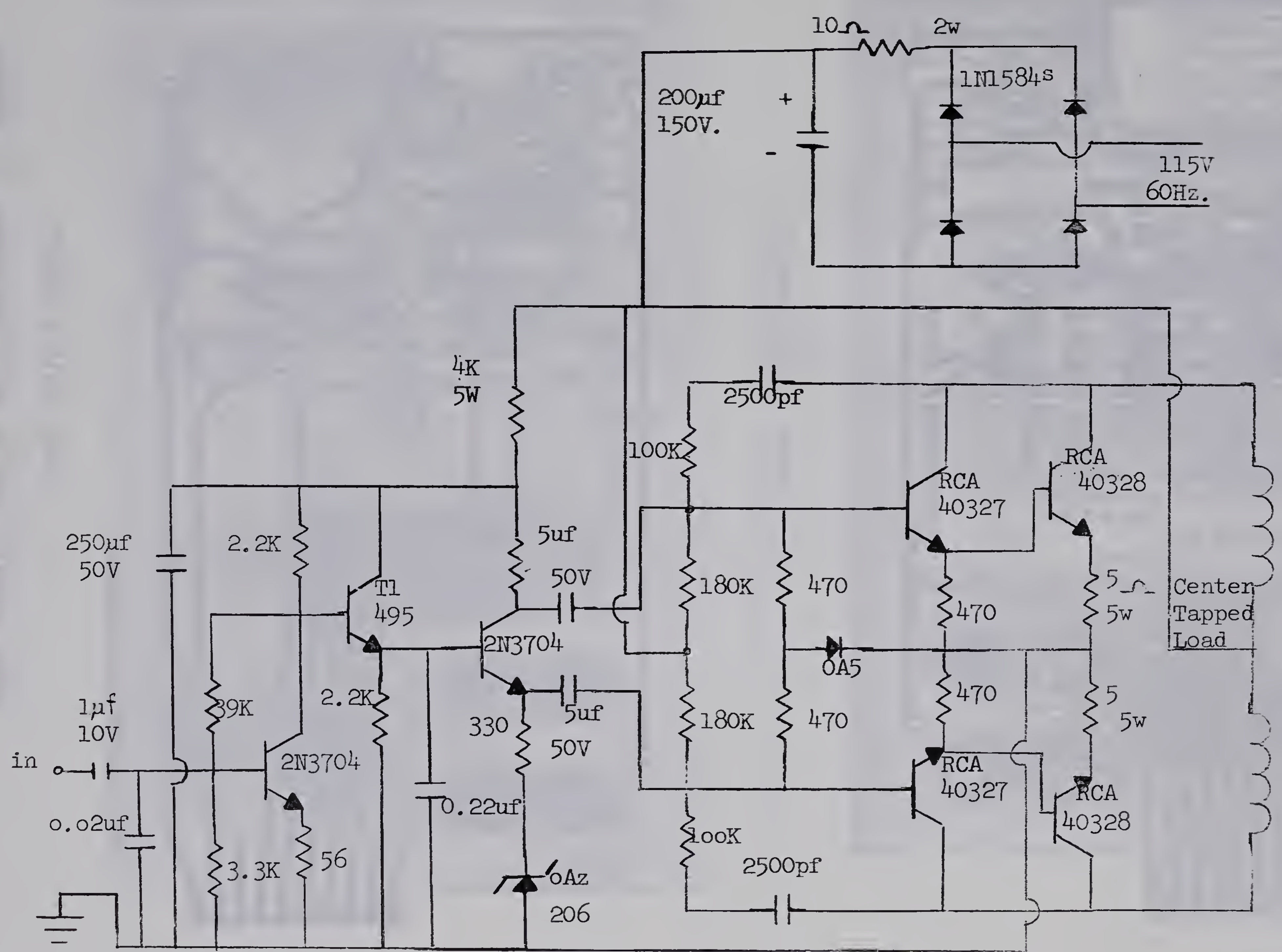

FIGURE 4.1 POWER AMPLIFIER CIRCUIT

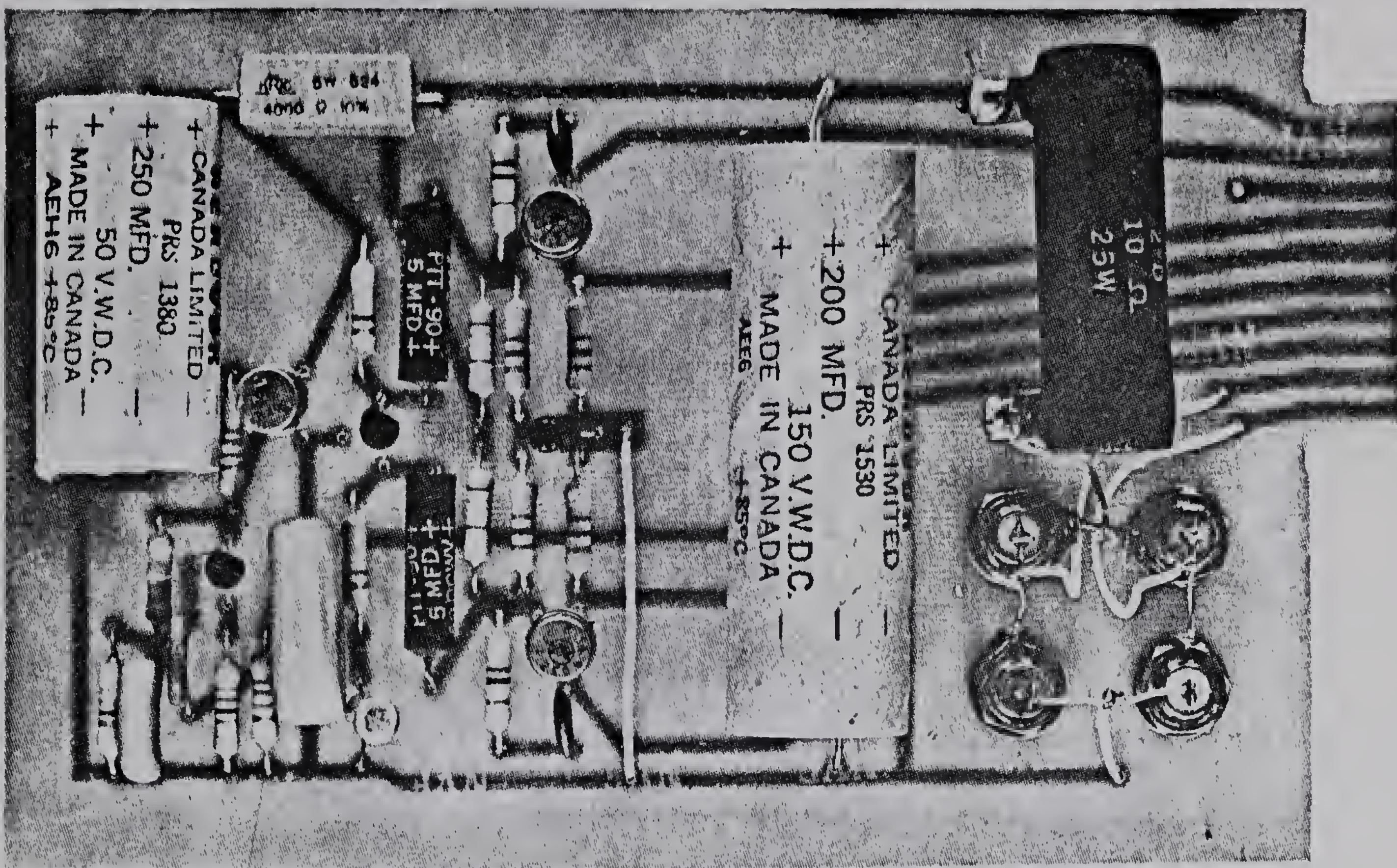

FIGURE 4.2(a) FRONT

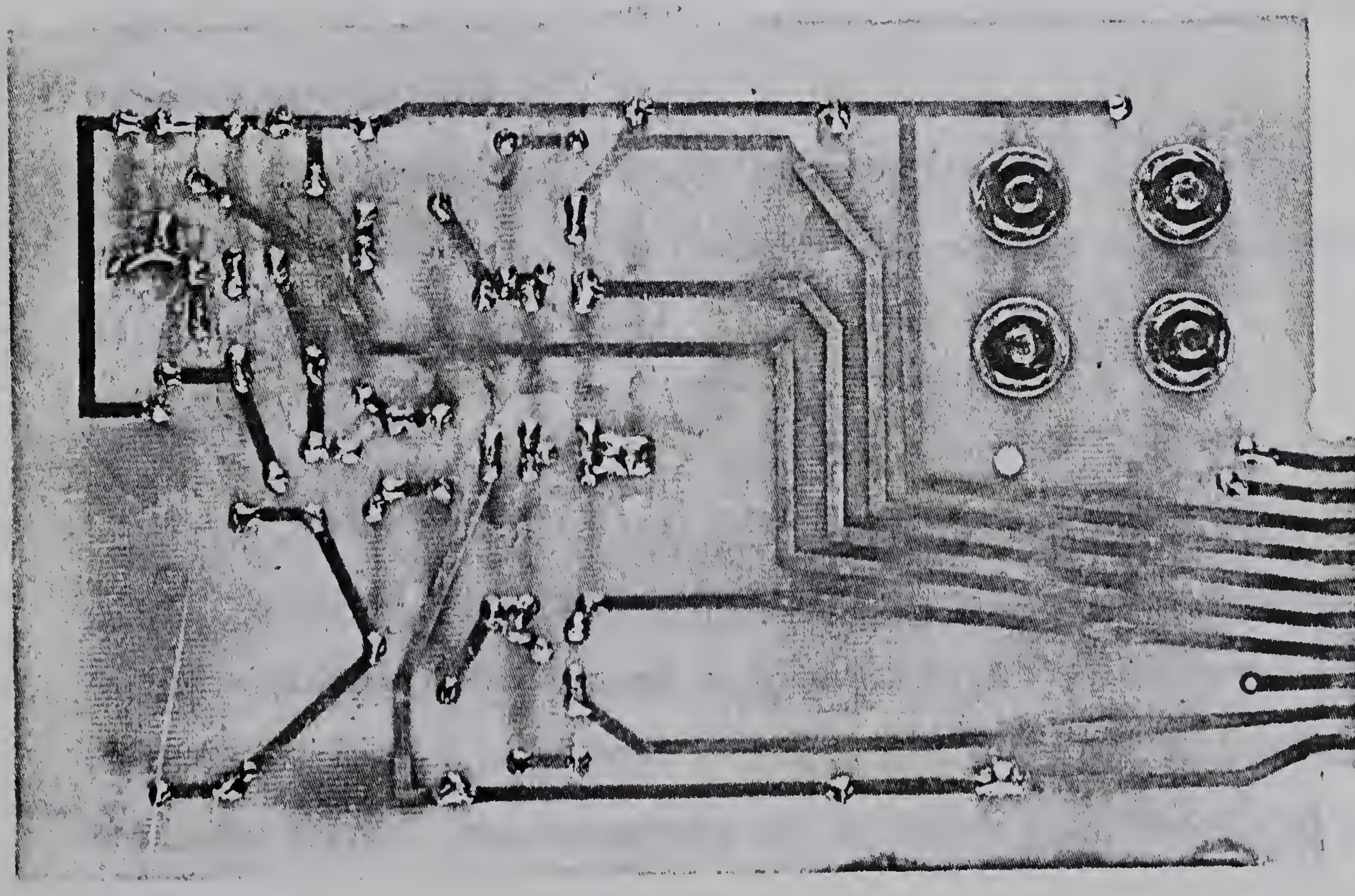

FIGURE 4.2(b) BACK

FIGURE 4.2 POWER AMPLIFIER PRINTED CIRCUIT BOARD

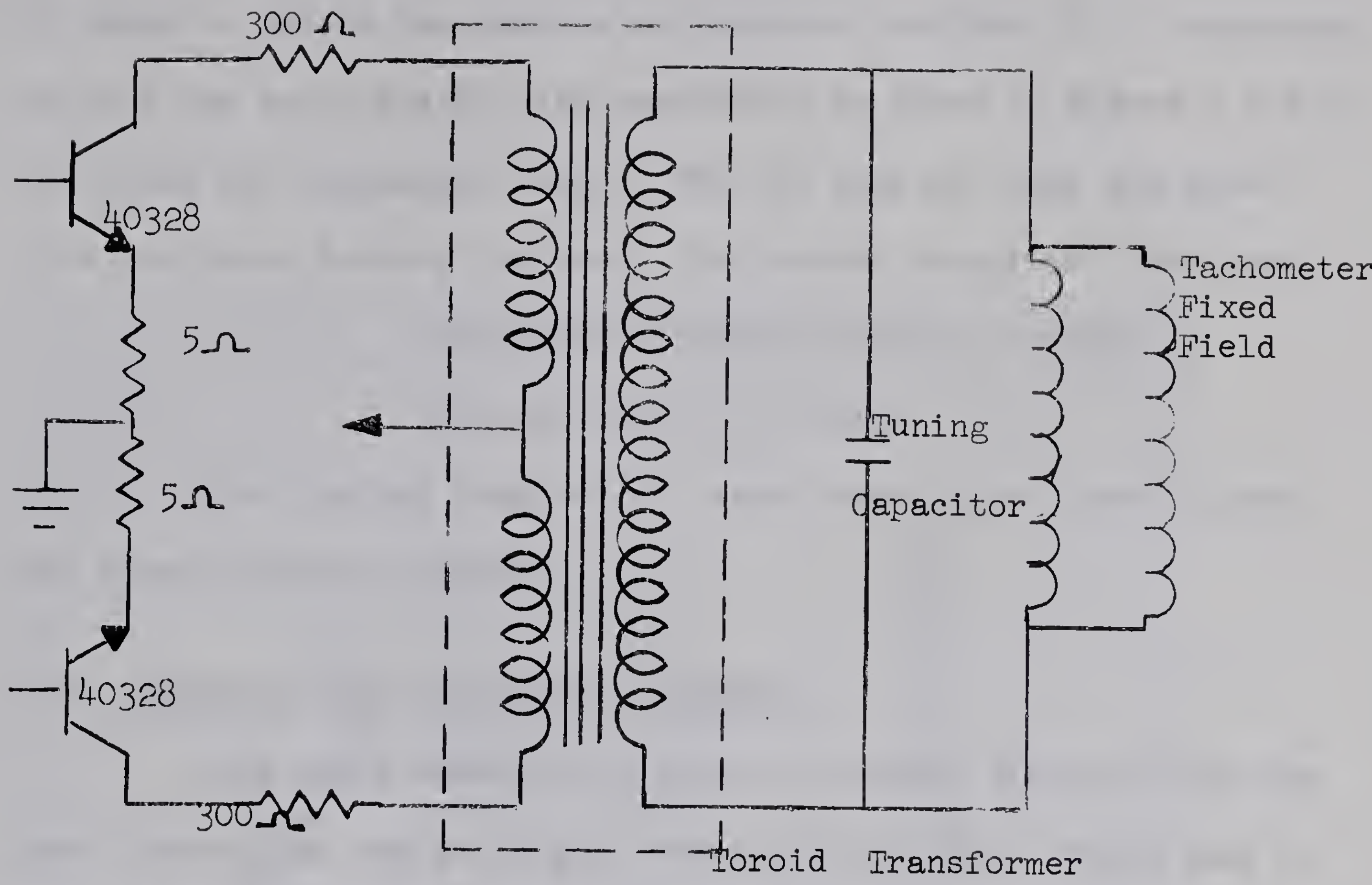

FIGURE 4.3 FIXED FIELD OUTPUT CIRCUIT

The toroid transformer, 300 ohm resistors, motor tuning capacitors, and output transistor emitter resistors are mounted on a separate external phenolic board.

The servo motor tachometer fixed field is operated in parallel with the motor fixed field so that a third power amplifier is not required for this field.

4.2 SERVO MOTOR

The servo motor is a G-M Laboratories Mark 12, Model 0, 115 volt, 400 Hz. servo motor with built in tachometer-generator. It has a minimum no-load speed of 4500 R.P.M., a stalled torque of 1.45 in-oz., and a tachometer output of 3.2 volts R.M.S. (400Hz.) per 1,000 R.P.M.. The motor body is $3\frac{1}{4}$ inches long, and $1^{7}/16$ inches in diameter.

In order to obtain the damping and response desired, it is necessary to tune the motor fields with capacitors as shown in Figure 4.3 for the fixed and tachometer fields. This is done by trial and error with the motor driving the load. The tuning capacitors used are:

Fixed and tachometer field -0.33µf

Control field -0.17µf

The output shaft of the servo motor fits directly into the speed reduction gearbox.

4.3 GEARTRAIN AND LEADSCREW ASSEMBLY

The speed reduction gearbox is coupled directly onto the servo motor body and has a gear ratio of 24:1. A 120 tooth gear is mounted on the gearbox output shaft. This provides an overall speed reduction of 12:1. The leadscrew has a linear travel of 8-5/8 inches and a pitch of 0.46 inches per revolution. This results in a maximum practical probe speed of about 2.5 inches per second.

Ball bearings are used in the motor, geartrain, and on the leadscrew shaft. The assembly is fitted to minimize backlash, friction, and inertia.

In order to prevent possible damage due to the motor stalled at the end of the leadscrew travel and over heating or over running the leadscrew travel and damaging the vertical position output potentiometer, limit switches are provided at the ends of the leadscrew travel to shut off the control signal to the servo motor when the end of travel is reached.

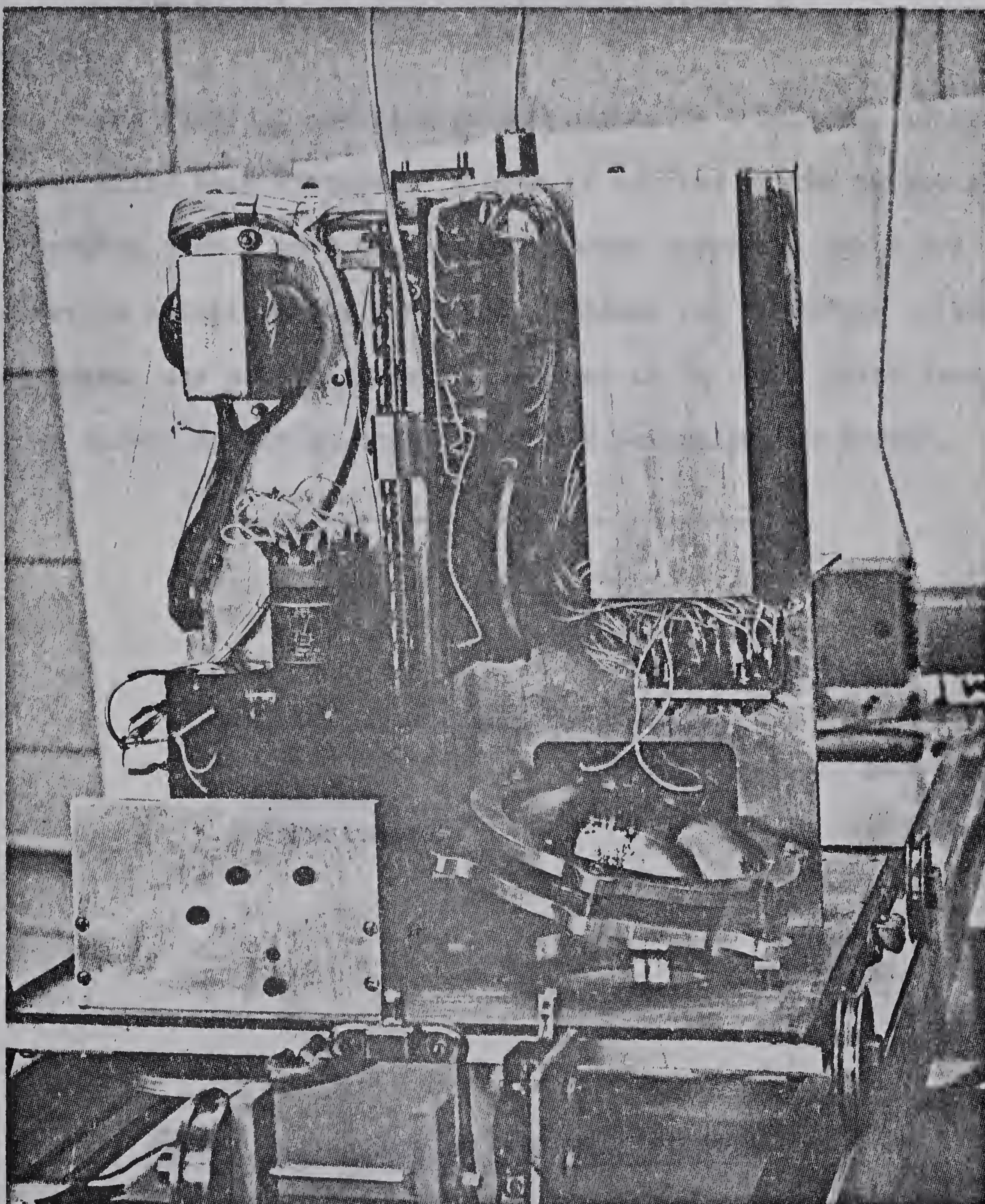

FIGURE 4.4 PROBE POSITIONING MECHANISM

4.4 VERTICAL POSITION POTENTIOMETER

Figure 4.4 shows the servo motor, geartrain and leadscrew, limit switches, probe, and vertical position output potentiometer arrangement.

The vertical position potentiometer is a 10K ohm, 10 turn, 0.05% linearity Borg Micropot. A gear is mounted on the output shaft, and it meshes with a gear in the servo motor geartrain for a 2:1 leadscrew to potentiometer gear ratio. Since the leadscrew is limited to 18½ turns, the potentiometer is limited to 9¼ turns which leaves a 3/8 turn safety margin at each end of the potentiometer travel.

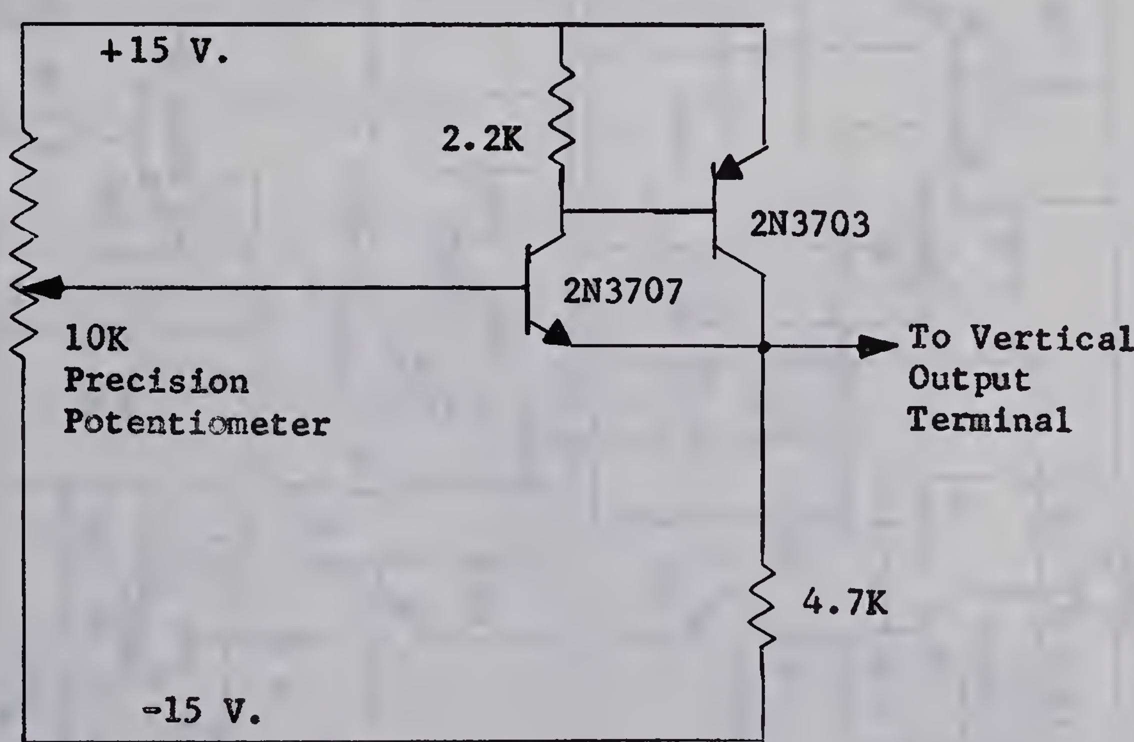

FIGURE 4.5 VERTICAL POSITION CIRCUIT

The compound transistor emitter follower circuit has an input impedance in the order of 10M ohms, and therefore does not load the precision potentiometer significantly. The output linearity is of the order of 0.1% full scale, and is within the accuracy of the probe assembly.

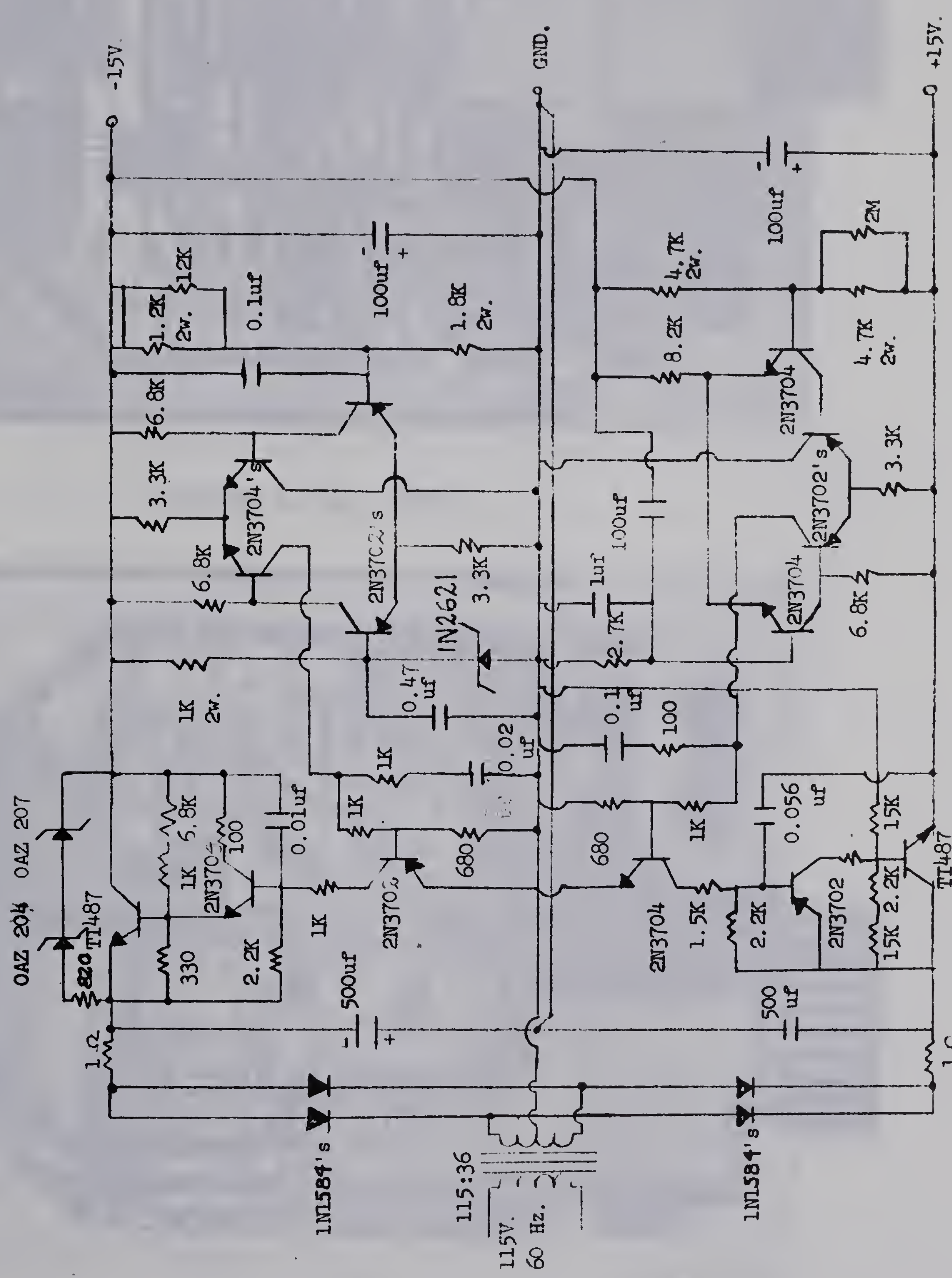

FIGURE 4.6 DUAL D.C. POWER SUPPLY CIRCUIT

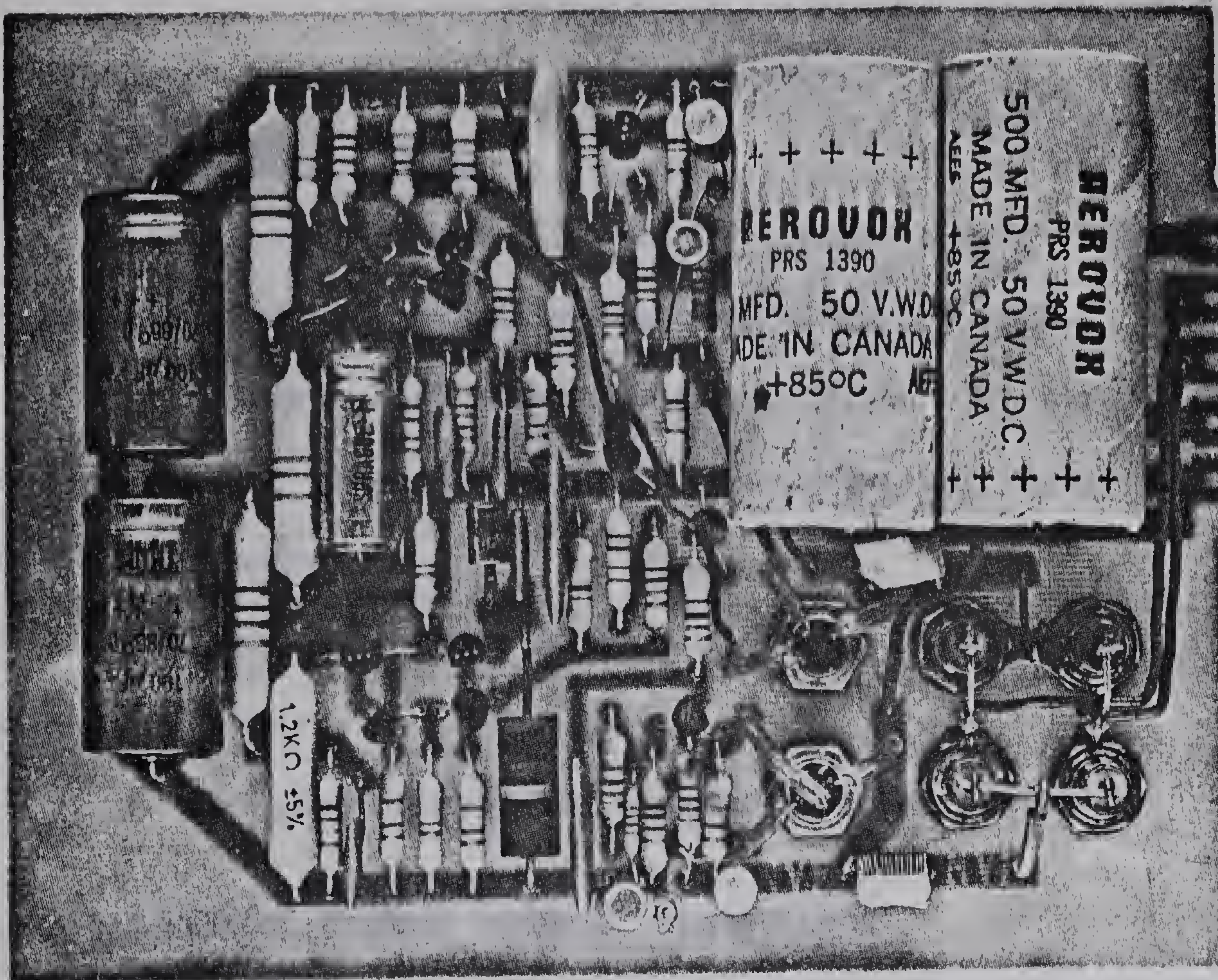

FIGURE 4.7(a) FRONT

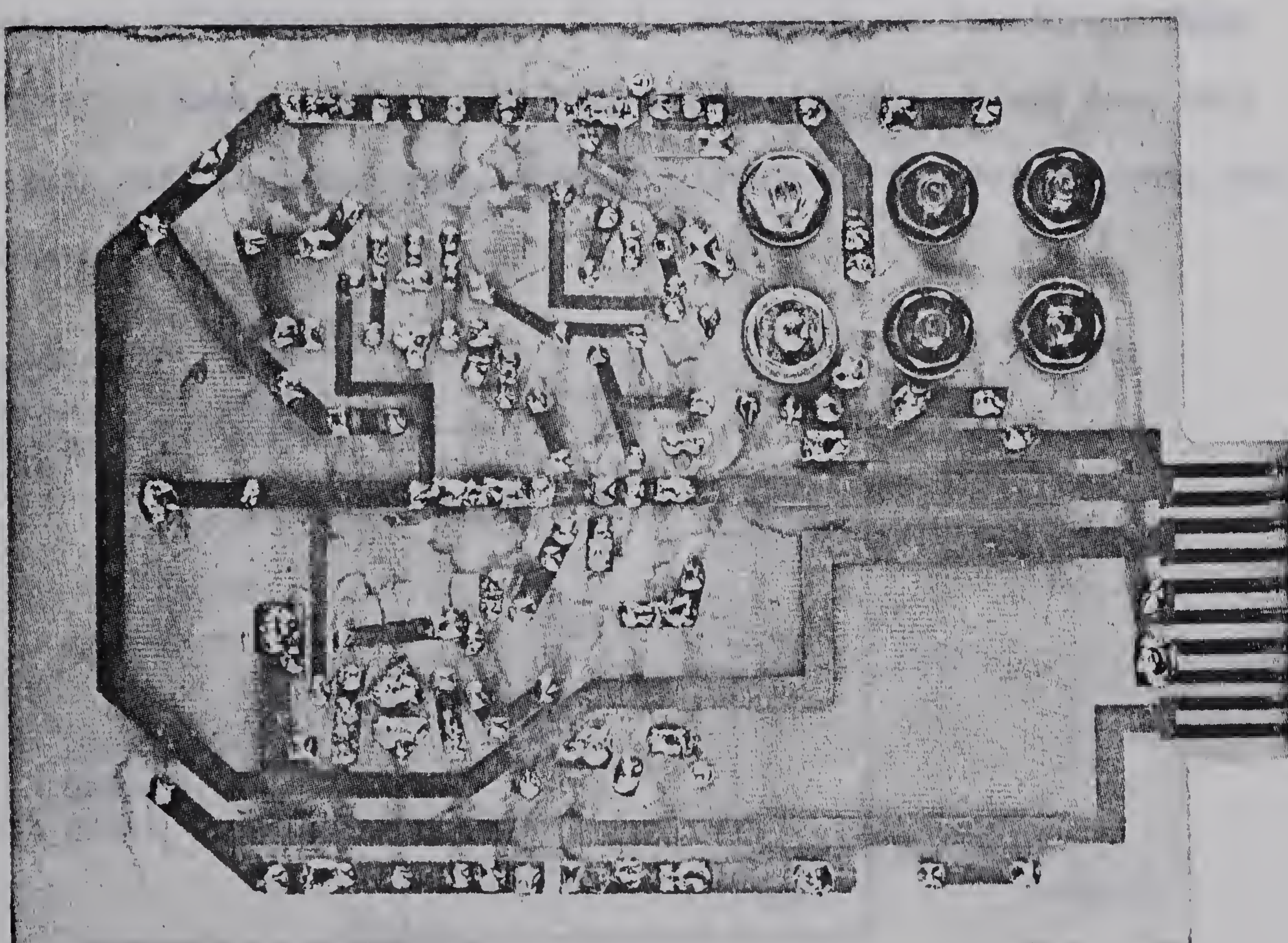

FIGURE 4.7(b) BACK

FIGURE 4.7 DUAL D.C. POWER SUPPLY PRINTED CIRCUIT BOARD

4.5 D.C. POWER SUPPLY

The +15, 0, and -15 volt D.C. power supply circuit is shown in Figure 4.6, and is relay coupled to the load.

Figure 4.7(a) shows the front of the D.C. power supply printed circuit board and Figure 4.7(b) shows the layout of the back of the board.

The 115:36 volt, 60 Hz centretapped transformer is mounted separately on the trolley.

The power supply has a maximum output of 150 ma.

4.6 TACHOMETER OUTPUT SIGNAL DEMODULATOR

The tachometer output signal is a 400 Hz sine wave that is amplitude modulated corresponding to the speed and direction of rotation of the servo motor. It is necessary to demodulate this signal, recover the low frequency modulating signal and feed this signal back into the motor control circuit to improve response and stability.

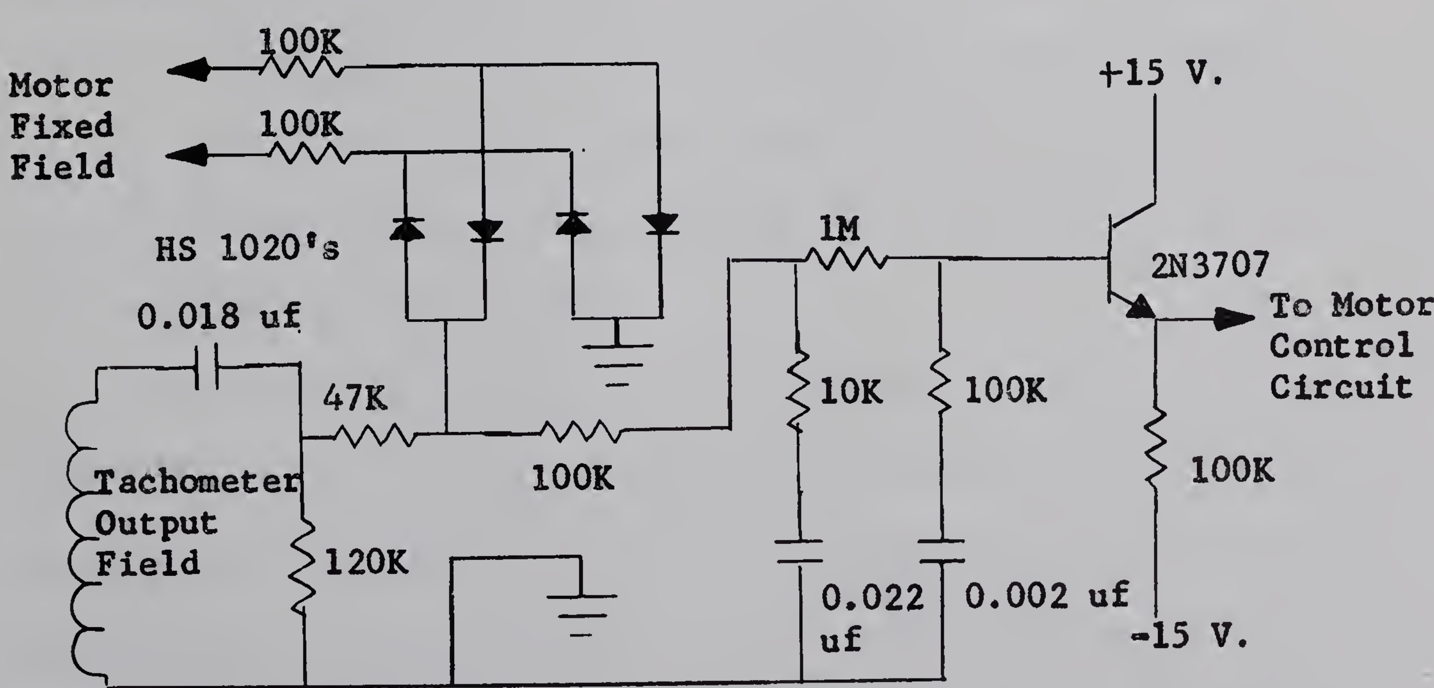

FIGURE 4.8 TACHOMETER SIGNAL DEMODULATOR CIRCUIT

The diode bridge used as the demodulator is shown in Figure 4.8. The servo motor fixed field 115V R.M.S. 400 Hz. voltage is used as the demodulating signal in order to recover polarity as well as magnitude from the tachometer signal. The 100K ohms resistors on the fixed field input to the bridge are for current limiting.

A high pass network is used on the tachometer signal input to match the phase of the fixed field and tachometer input voltages.

The bridge produces a half wave rectified output, either positive or negative, depending on the phase of the input signal. Two low pass networks in series attenuate the high frequency components of the output and the emitter follower provides impedance matching for a low output impedance.

This circuit produces a voltage proportional to the servo motor speed, negative for upward probe motion, and positive for downward.

CHAPTER FIVE

LIGHT SOURCE AND LIGHT SOURCE CONTROL CIRCUIT

5.1 THE LIGHT SOURCE

Various types of light sources were investigated, including small bulbs mounted near the end of the probe. This arrangement provided a suitable constant light intensity on the surface without any additional control circuit. The disadvantages were that the weight of the bulbs and mounting apparatus adversely affected system stability and that making a lightweight, waterproof mounting assembly for mounting the bulbs on the probe that did not cause turbulance presented quite a problem. The other type of light source investigated was a large lamp mounted on the trolley with a light sensor circuit and a control circuit to provide a constant light intensity on the surface. The advantages of this arrangement were that the River Plotter could be self-starting and that elaborate waterproofing schemes were not required. The disadvantages were that a light intensity sensor circuit and a control circuit were required, however, this latter type of light source was finally selected.

The River Plotter light source is a four inch diameter, 12 volt, sealed beam spotlight lamp #4055. At maximum light intensity it dissipates about 35 watts.

A sealed beam unit is used because it produces a concentrated beam of light of sufficient intensity to provide the desired level of surface illumination even when the system is working in slightly murky water . Since operating in water causes reflection and refraction problems, the lamp is mounted as close to the center line of the probe travel as possible, so that the light strikes the water surface

at very nearly a 90 degree angle. The lamp is aimed so that the probe always operates in an area of maximum surface illumination.

5.2 THE LIGHT SOURCE CONTROL CIRCUIT

As described in section 2.2 the light intensity of a surface varies inversely as the distance from the light source to the surface changes. Since the light source in the River Plotter is fixed and the distance to the surface varies, it is necessary to control the intensity of the light source to obtain a constant level of surface illumination.

The light sensor circuit is described in section 2.2, and the light source control circuit is shown in figure 5.1. The reference input sets the desired level of surface illumination and has a gain of -1 through the four transistor operational amplifier. The light sensor input network has a gain of -1 except for positive inputs which are limited by the Zener diode to a maximum of about 6.2 volts to ensure that the lamp will light when the system is turned on.

The output of the operational amplifier connects to the base of the PNP transistor which acts as a current source and charges up the capacitor C1. When the voltage across C1 reaches the unijunction firing voltage, the unijunction fires, and a voltage is applied to the gate of the SCR, causing the SCR to conduct, The diode bridge then also conducts and the current flows through the light source lamp. The voltage input to the lamp is therefore a full-wave rectified 60 Hz signal that has some of the leading part of each half cycle blocked by the SCR as shown in figure 5.2.

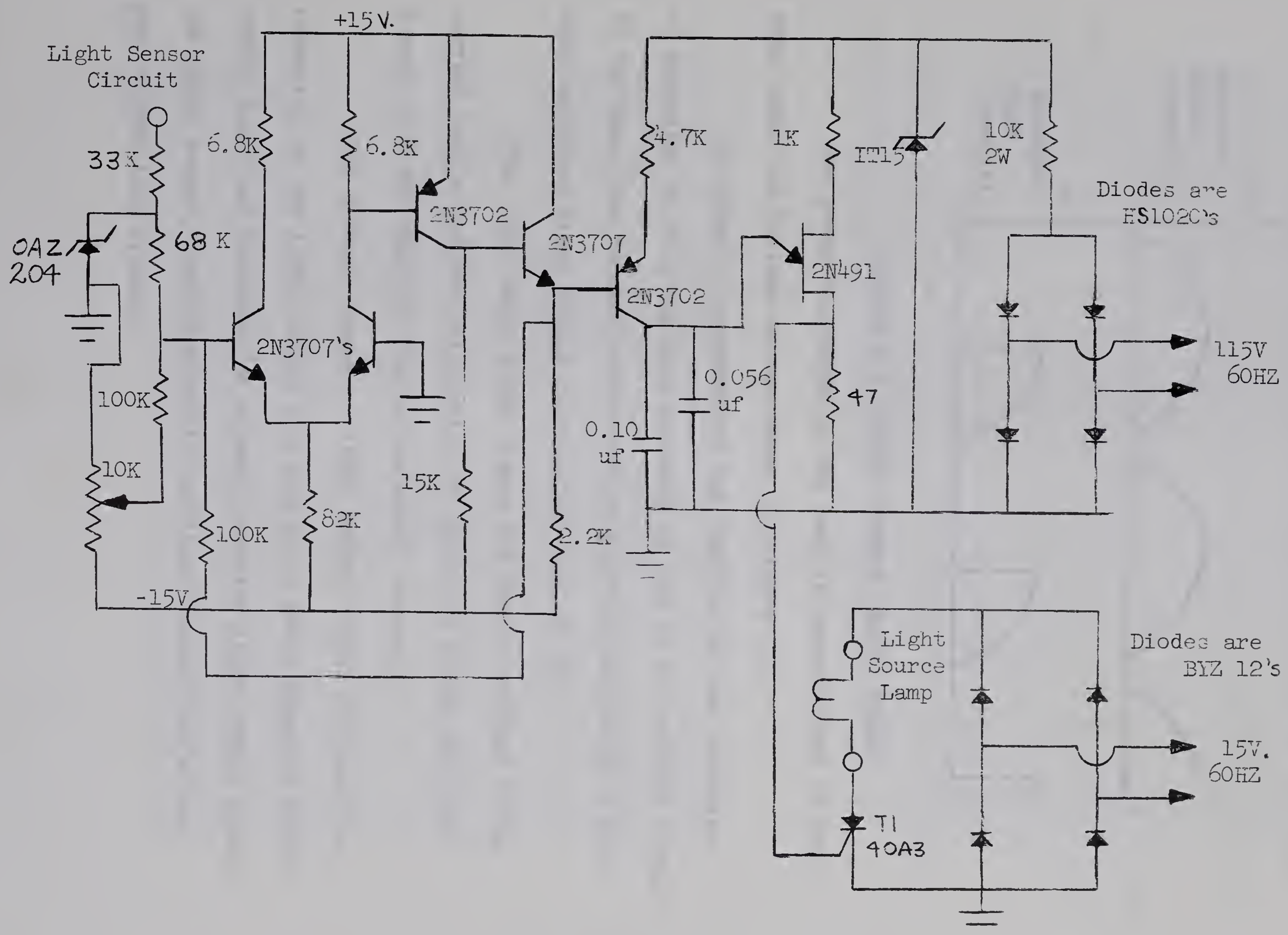

Figure 5.1 LIGHT SOURCE CONTROL CIRCUIT

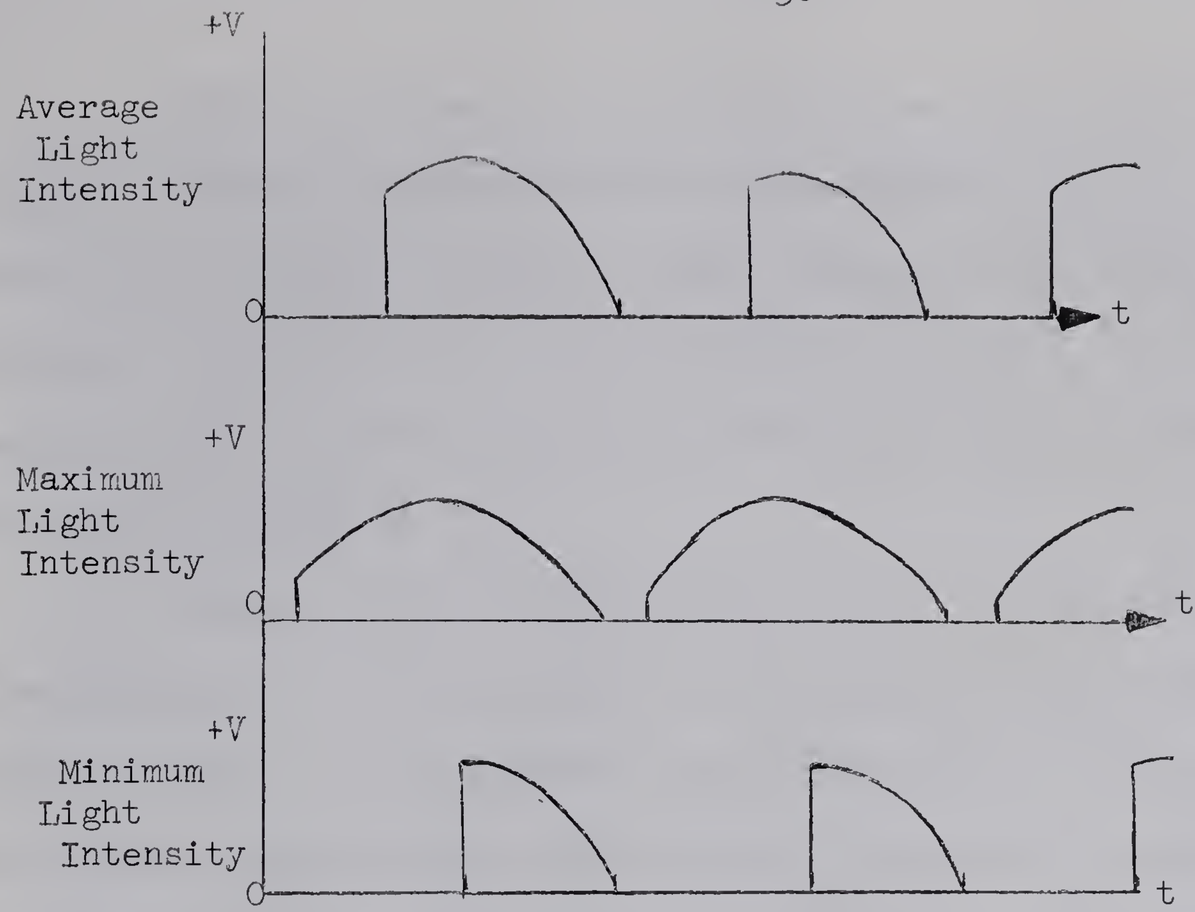

FIGURE 5.2 LIGHT SOURCE WAVE FORMS

The power delivered to the lamp is proportional to the area under the voltage curves shown in Figure 5.2.

In order to synchronize the starting of the charging of capacitor C1 with the zero crossing of the 60 Hz. voltage supply to the lamp ,the current source and unijunction are fed by a full wave rectifier diode bridge supplied by 115V, 60 Hz..

The 1T15 Zener diode clamps the supply voltage to the current source and the unijunction at about +15 volts, and the 2 watt 10K ohm resistor limits the supply current.

For a small change in light sensor output voltage, the intensity of the light source will dim for a small negative light sensor input and brighten for a small positive light sensor input, the light sensor, control circuit, and light source form a high gain closed loop system.

Since the filament of the light source has a relatively long time constant, these "pulses" of power do not cause much light source flicker except at minimum light intensity. The system is therefore adjusted so that minimum intensity is beyond the normal operating range, and the stability of the River Plotter is therefore not adversely affected.

Figure 5.3(a) shows the front of the printed circuit board which contains the two light sensor circuits and the light control circuit as well as the tachometer signal demodulator, horizontal and vertical output potentiometer circuits, and a towing speed reduction circuit which is discussed in Chapter 7. Figure 5.3(b) shows the layout of the back of this board.

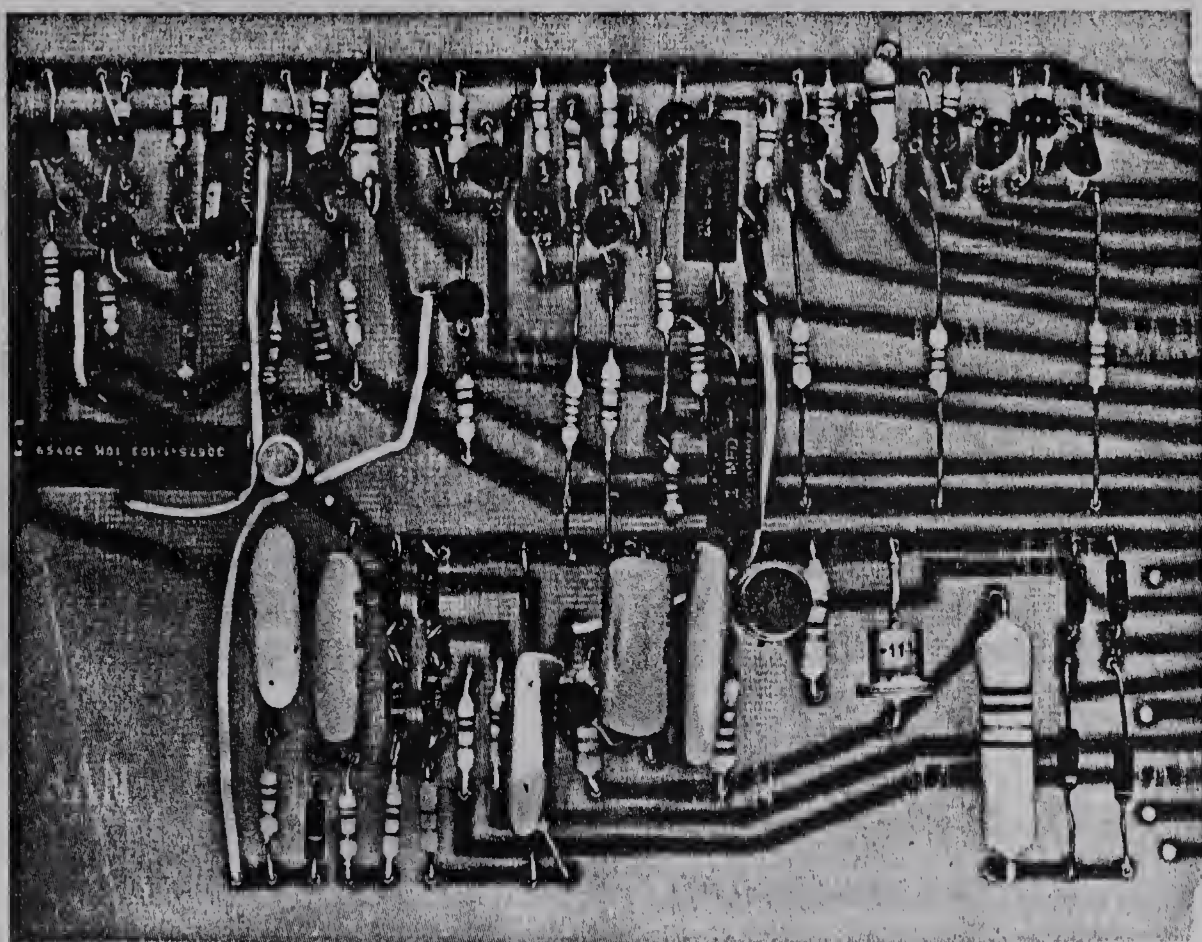

FIGURE 5.3(a) FRONT

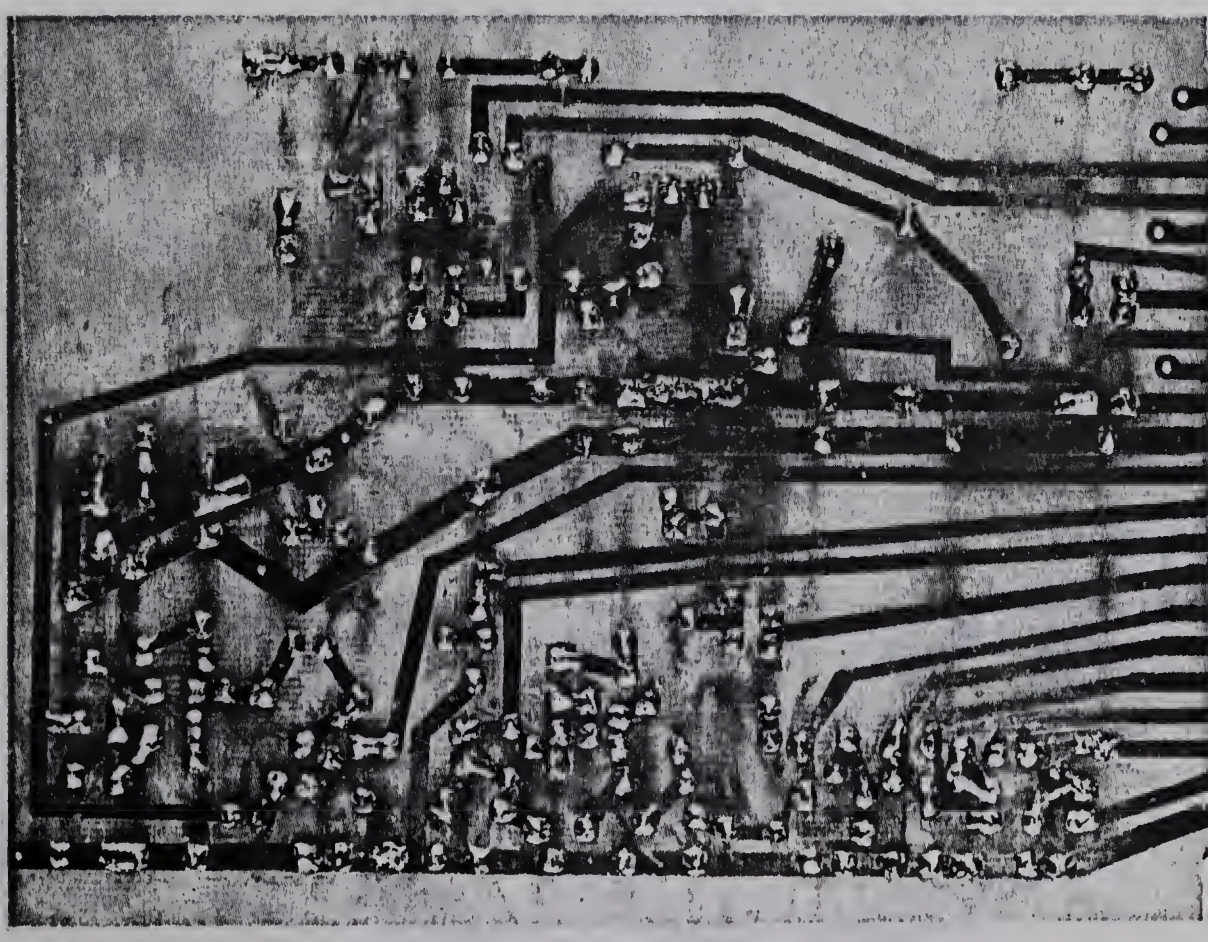

FIGURE 5.3(b) BACK

FIGURE 5.3 MISCELLANEOUS CIRCUITS PRINTED CIRCUIT BOARD

CHAPTER SIX

TOWING MOTOR AND HORIZONTAL POSITION OUTPUT CIRCUIT

6.1 TOWING MOTOR

The River Plotter trolley is towed back and forth along the rails by a towing motor as shown in Figure 1.2. The towing motor is a Kollsman Model 890-115V-60 Hz., two phase motor. The motor output shaft is connected directly to a Link Aviation gearbox with a gear ratio of 100:1. A 1-5/8 inch diameter pulley is mounted on the gearbox output shaft, and the towing line for the trolley is wrapped one turn around this pulley.

A towing line return pulley is mounted at the far end of the rails from the towing motor. The two ends of the towing line are connected to the towing eyes on the trolley as shown in Figure 6.1.

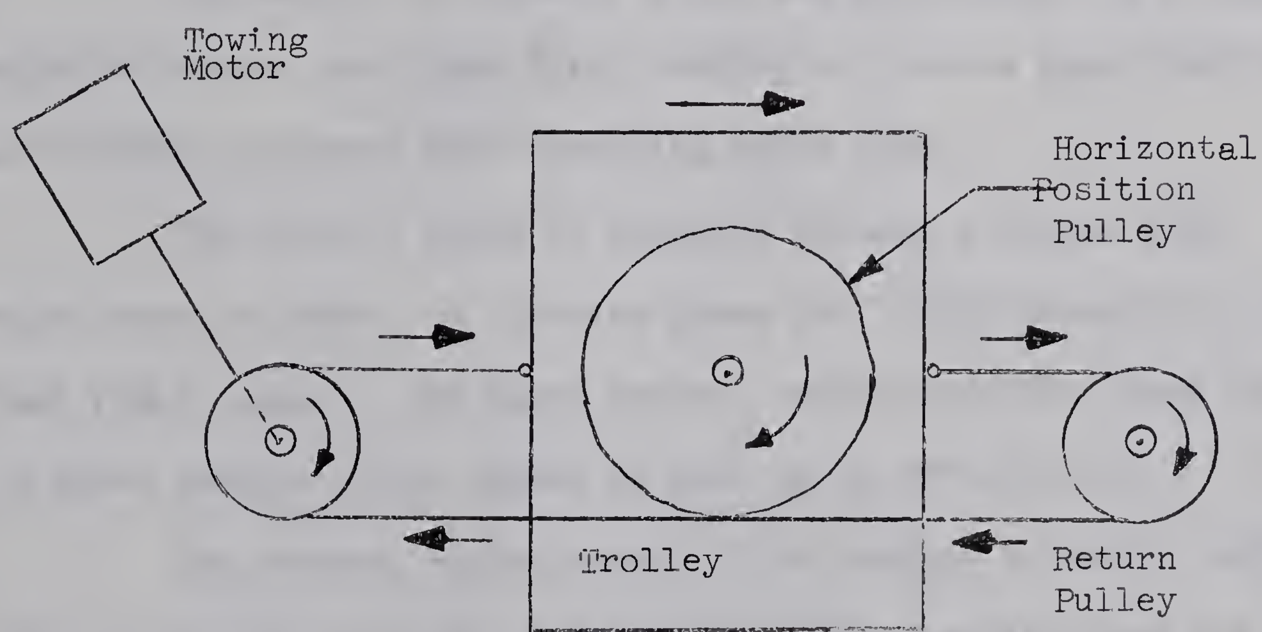

FIGURE 6.1 TOWING SCHEMATIC

The motor fixed field is fed directly from the secondary of the 163B 60 transformer as shown in Figure 6.2.

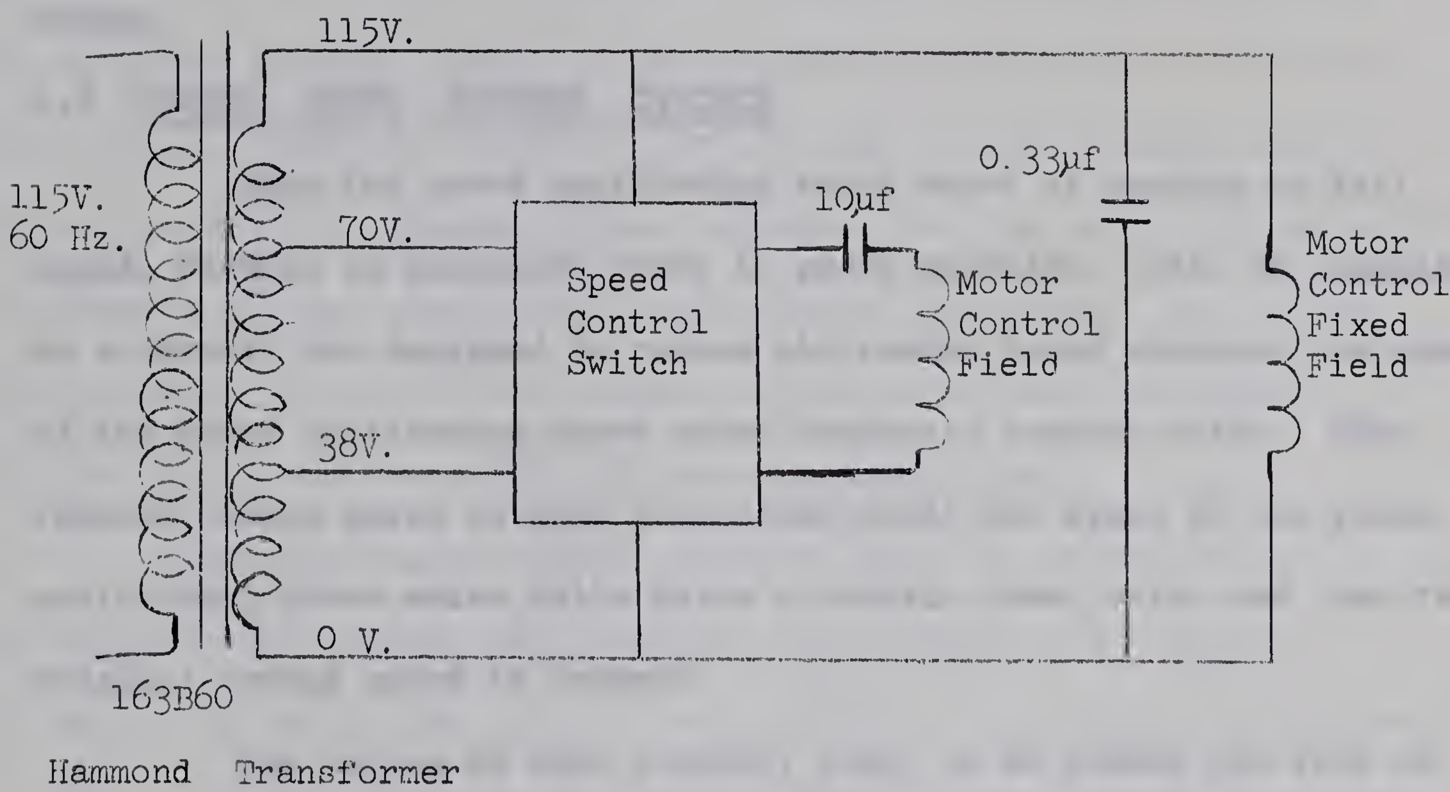

FIGURE 6.2 TOWING MOTOR SCHEMATIC

The motor is tuned by trial and error with the 0.33µf capacitor across the fixed field winding to produce good starting and stopping response when operating under load.

The control field is supplied through a series 10µf capacitance in order to provide phase shift with respect to the fixed field signal. The speed control switch provides three forward and three reverse motor speeds as well as an OFF position.

The maximum towing speed of the trolley is about two inches per second with the 1 5/8 inch diameter pulley, and the motor requires 0.60 amps. at this speed.

Towing speeds in excess of four inches per second could be obtained simply by increasing the diameter of the pulley, however,

when plotting a fairly rough surface, accuracy would get progressively worse as the speed increased due to the increased surface rate of change.

6.2 TOWING SPEED REDUCER CIRCUIT

When the probe positioning servo motor is running at full speed, there is an excessive error in probe position. This is undesireable, so a circuit was designed to reduce the towing speed whenever the speed of the probe positioning servo motor reaches a certain value. This reduced towing speed is then maintained until the speed of the probe positioning servo motor falls below a certain lower value and then the original towing speed is resumed.

The action of this circuit, then, is to reduce the rate of change of the surface when this rate of change reaches a value which results in an excessive tracking error.

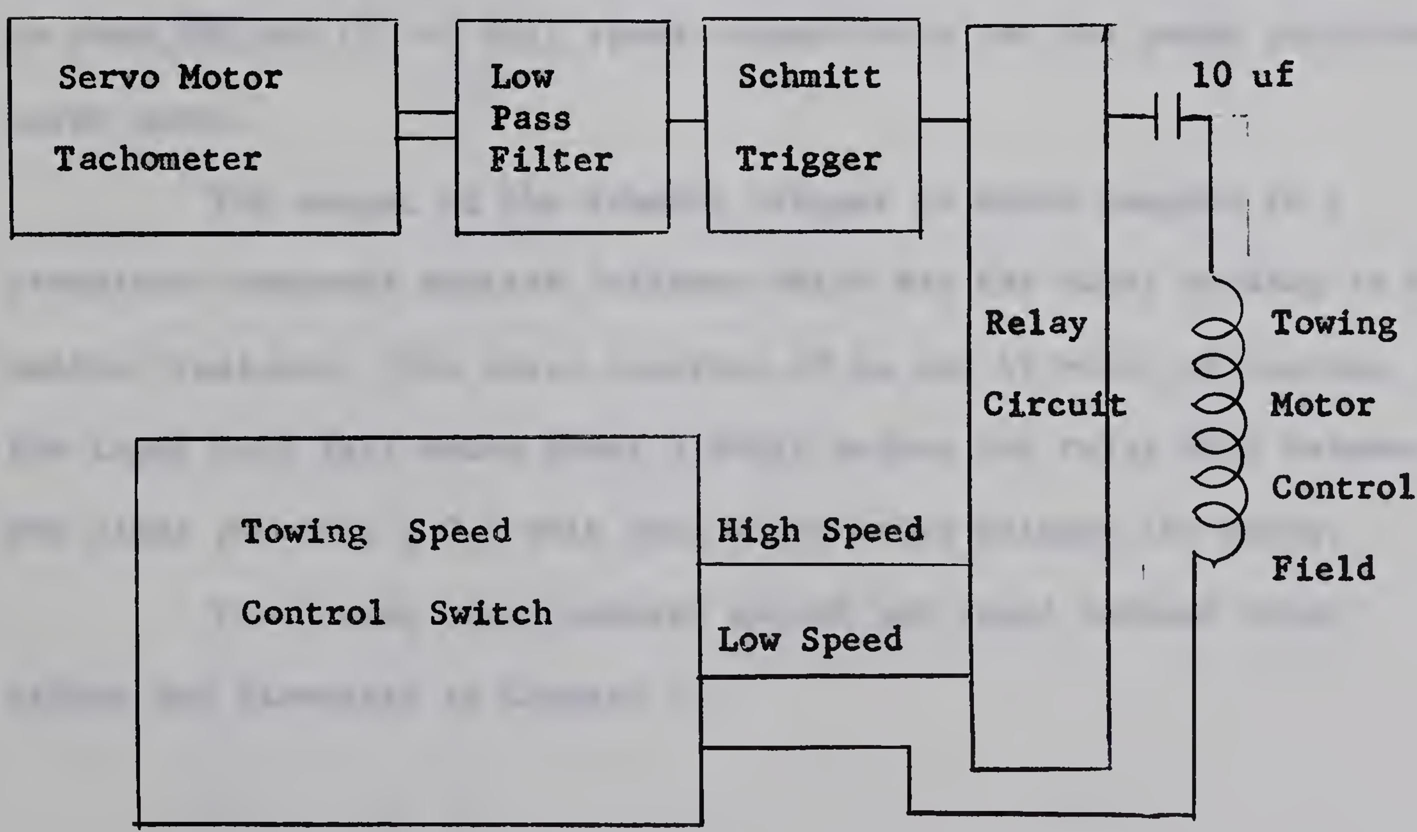

FIGURE 6.3 BLOCK DIAGRAM OF TOWING SPEED REDUCER

In Figure 6.3, the probe positioning servo motor tachometer output is a 400 Hz sine wave with an amplitude proportional to the speed of the servo motor. This is rectified and fed into a low pass filter which produces a D.C. output voltage proportional to the servo motor speed. When the output of the low pass filter exceeds about 5 volts, the Schmitt trigger circuit switches and the change in output of the Schmitt trigger causes the relay circuit to operate. The towing speed control switch has two separate leads, one being for high or regular speed, and the other for low or reduced speed.

When the relay circuit operates, the low speed lead is connected to the towing motor control field and when the circuit releases, the high speed lead is re-connected. The relay circuit does not release until the input to the Schmitt trigger drops below three volts. The level at which the relay circuit operates and releases corresponds to about 30% and 15% of full speed respectively for the probe positioning servo motor.

The output of the Schmitt trigger is diode coupled to a transistor compound emitter follower which has the relay winding as the emitter resistor. The relay requires 20 ma and 12 volts to operate and the input must fall below about 3 volts before the relay will release. The diode provides a 0.5 volt drop which helps release the relay.

The towing speed control switch and speed reducer relay wiring are discussed in Chapter 7.

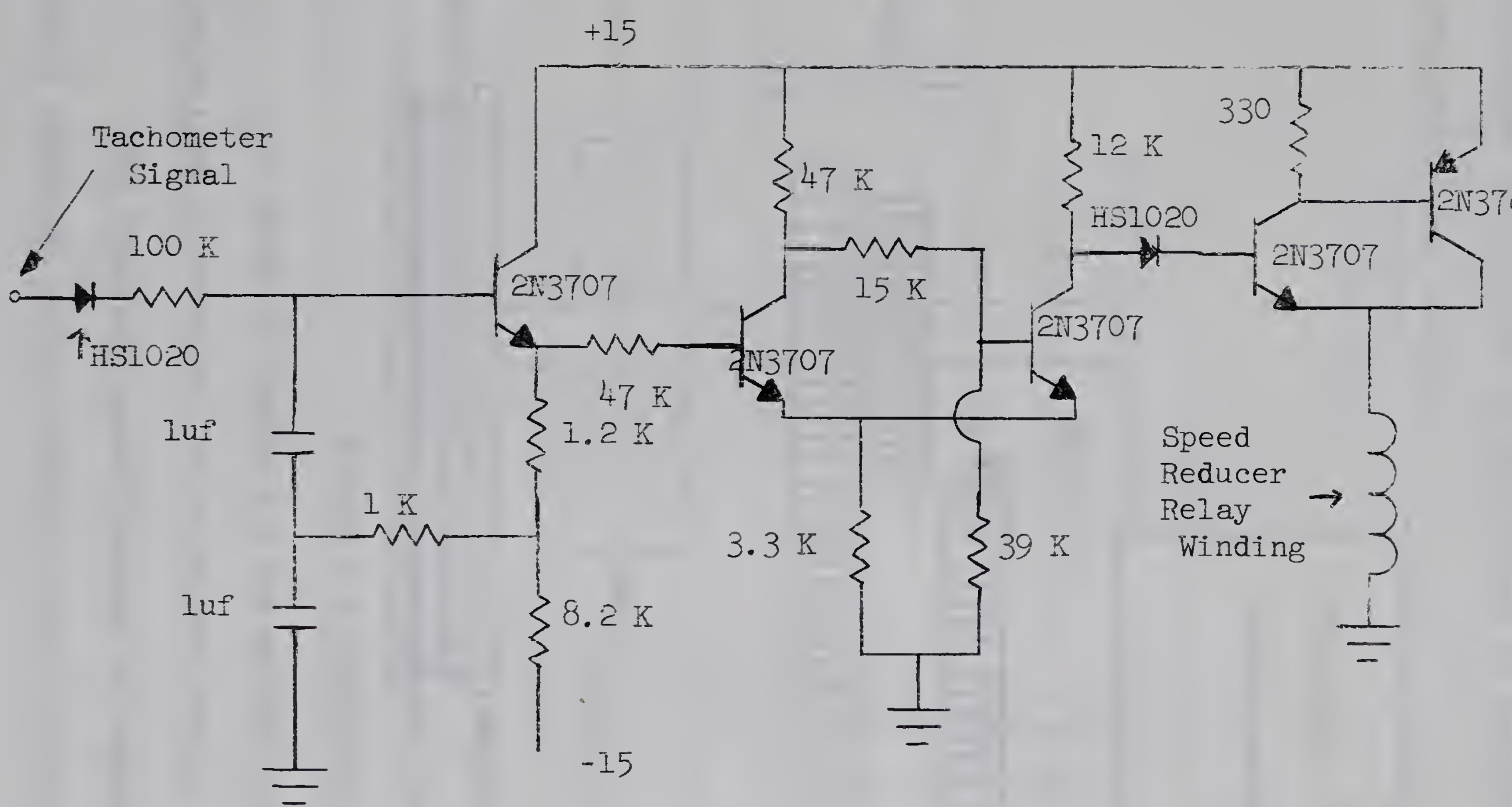

FIGURE 6.4 TOWING SPEED REDUCER CIRCUIT

6.3 HORIZONTAL POSITION OUTPUT CIRCUIT

Figures 6.1 and 6.5 show the horizontal position pulley which is mounted on the trolley. The returning towing line passes underneath the trolley and is wrapped one turn around this pulley, therefore, as the trolley is towed along, this pulley is rotated. The amount of rotation of the pulley is proportional to the distance travelled by the trolley.

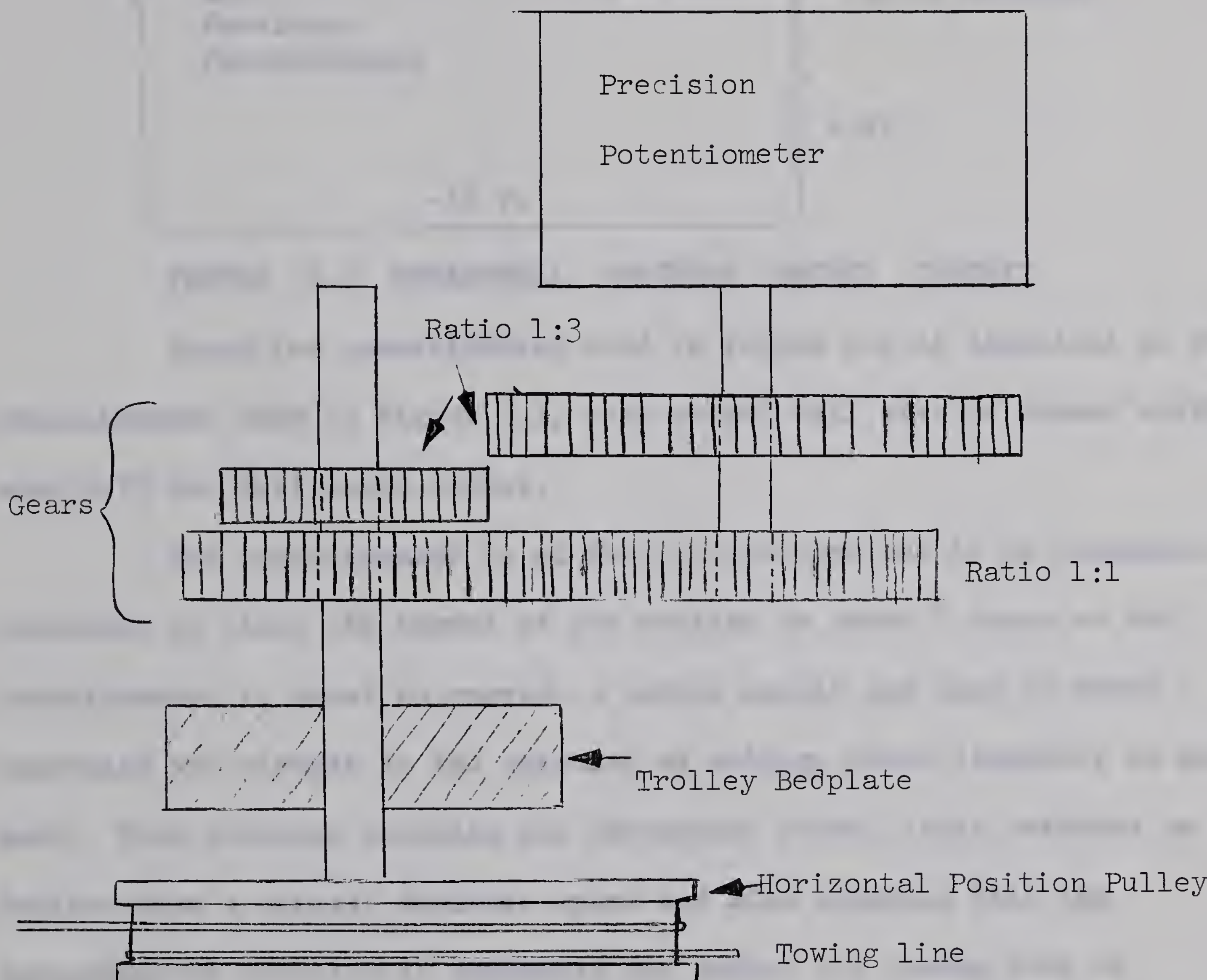

FIGURE 6.5 HORIZONTAL POSITION ASSEMBLY

As shown in Figure 6.5 the pulley is mounted on a shaft which drives a precision potentiometer through a gear arrangement.

The precision potentiometer is incorporated in an output circuit identical to the vertical output circuit shown in Figure 4.5,

which is again included here as Figure 6.6.

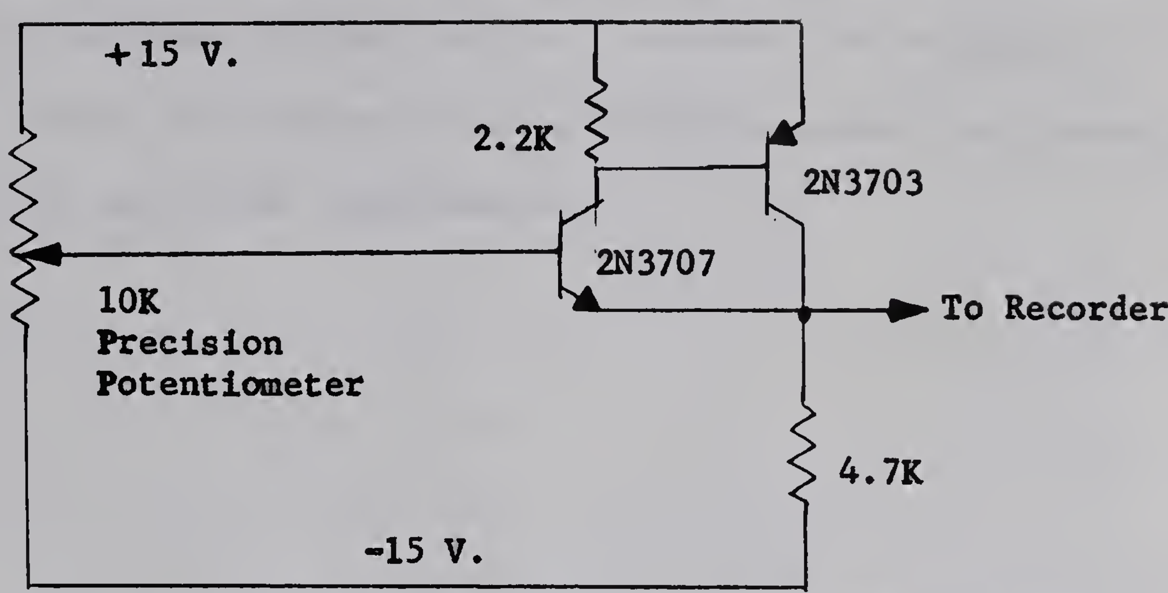

FIGURE 6.6 HORIZONTAL POSITION OUTPUT CIRCUIT

Since the potentiometer used in Figure 6.6 is identical to the potentiometer used in Figure 4.5, this output will also be linear within about 0.1% for full scale travel.

The potentiometer is of the 10 turn type and it is therefore necessary to limit the travel of the trolley to about 9 turns on the potentiometer in order to provide a safety margin and also to avoid operating the circuit at the extremes of voltage where linearity is not good. This requires locating the horizontal travel limit switches no further than a certain distance apart and also ensuring that the potentiometer position is correctly set before the towing line is attached. The position is correct when the circuit output changes from +12.9 volts to -14.1 volts when the following distances are traversed by the trolley:

1:1 gear ratio: 53 inches = 4 feet, 5 inches

1:3 gear ratio: 159 inches = 13 feet, 3 inches

These two gear ratios are provided on the River Plotter trolley and one or the other can be selected simply by adjusting the proper pair of gears so that they mesh. The gears are selected so that the distance between shafts is constant and backlash is a minimum. Other gear ratios could be fitted to adjust the operating distance for particular requirements.

CHAPTER SEVEN

EXTERNAL CONTROLS

Although the River Plotter is designed to require a minimum of general supervisory effort on the part of the operator, some external controls are required. The control switches are mounted on the control box which is connected by a cable to the trolley and towing motor allowing the trolley to be remotely controlled.

The control box is shown in Figure 7.1.

7.1 OFF - ON SWITCH, FUSES AND INDICATOR LIGHTS

The OFF-ON switch controls all the power supplied to the River Plotter. The fuses and indicator lights are arranged as shown in Figure 7.2.

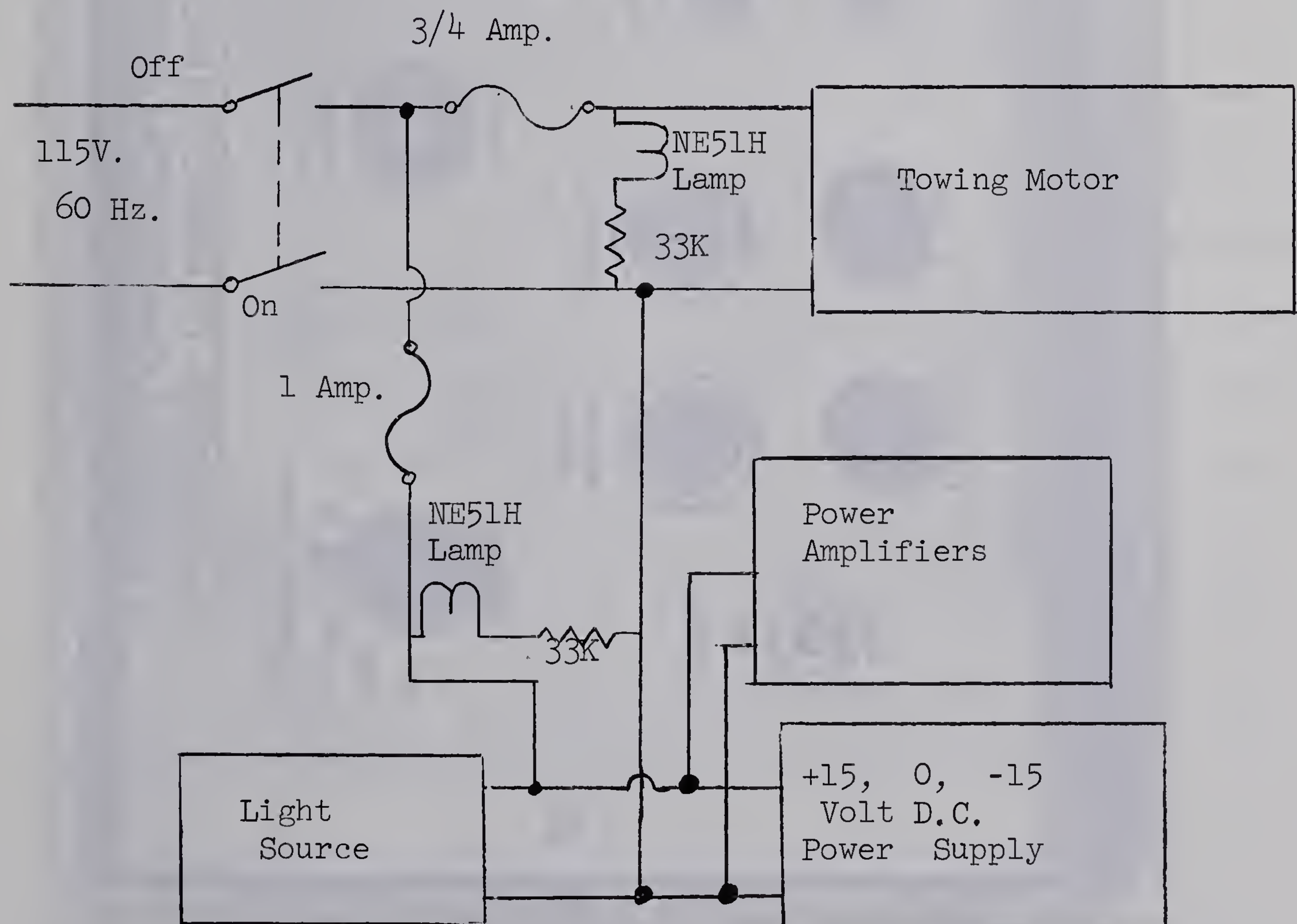

FIGURE 7.2 POWER DISTRIBUTION SCHEMATIC

FIGURE 7.1 CONTROL BOX


SHUT POWER OFF BEFORE DISCONNECTING
OR CONNECTING TROLLEY CABLE

7.2 TOWING SPEED SELECTOR AND TOWING MOTOR RESET SWITCHES

The towing speed selector switch is used to select one of seven towing conditions; three speeds each in Forward and Reverse, and a Stop or Off position. The associated circuitry includes the towing motor supply transformer, three relays, four limit switches, the towing motor reset switch, and the 10µf phase shifter capacitance as shown in Figure 7.3.

The general operation of the block diagram Figure 7.3, is that the towing speed control switch selects the speed and direction of trolley travel.

The towing speed reduction relay is controlled by the towing speed reduction circuit which acts to reduce a surface rate of change which would otherwise result in an excessive vertical position error as described in section 6.2. When the towing speed reduction relay operates, it reduces the towing speed to the next lowest speed. The horizontal limit switch relay is normally operated and in this position, passes the signal from the towing speed reduction relay to the towing motor control field. The horizontal limit switch relay is under the control of both the vertical and horizontal limit switches and also the towing motor reset switch. When either the horizontal or vertical limits of travel are reached, the horizontal limit switch relay is released, grounding both sides of the towing motor control field, and thus stopping the towing motor.

When this condition occurs, the operator must assume manual control to overcome this condition, after which the River Plotter can resume operation in the automatic mode.

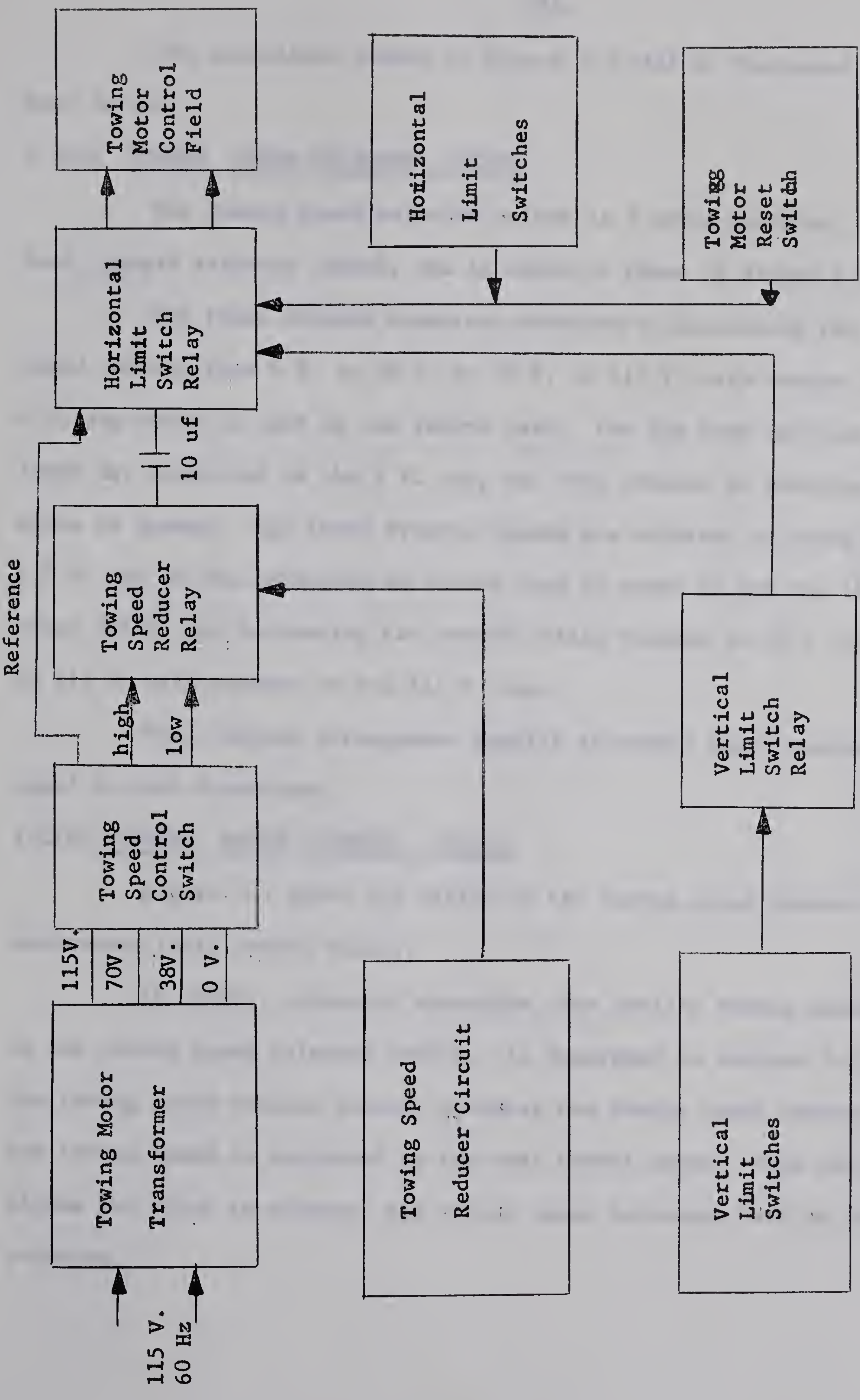

FIGURE 7.3 BLOCK DIAGRAM OF TOWING SPEED CONTROL

The individual blocks in Figure 7.3 will be discussed in more detail.

7.2(a) <u>TOWING SPEED SELECTOR SWITCH</u>

The towing speed selector switch is a seven position, three deck, ganged selector switch, and is wired as shown in Figure 7.4.

The three forward speeds are obtained by increasing the control field voltage from 0 V. to 38 V. to 70 V. to 115 V. with respect to the 0 V. tap which is used as the return lead. For the Stop position, both leads are connected to the 0 V. tap, and this amounts to shorting both sides to ground. The three reverse speeds are obtained by using the 115 V. tap as the reference or return lead in order to get the 180 degree phase shift, and increasing the control field voltage to 45 V. to 77 V. to 115 V. with respect to the 115 V. tap.

This tapping arrangement results in nearly equal increments of speed in both directions.

7.2(b) <u>TOWING MOTOR CONTROL RELAYS</u>

Figure 7.5 shows the wiring of the towing speed reducer and horizontal limit switch relays.

In normal, automatic operation, the trolley towing speed is set on the towing speed selector switch. As described in section 6.2, when the towing speed reducer circuit operates the towing speed reducer relay, the towing speed is decreased to the next lowest speed. When the circuit allows the relay to release, the towing speed increases back to the speed selected.

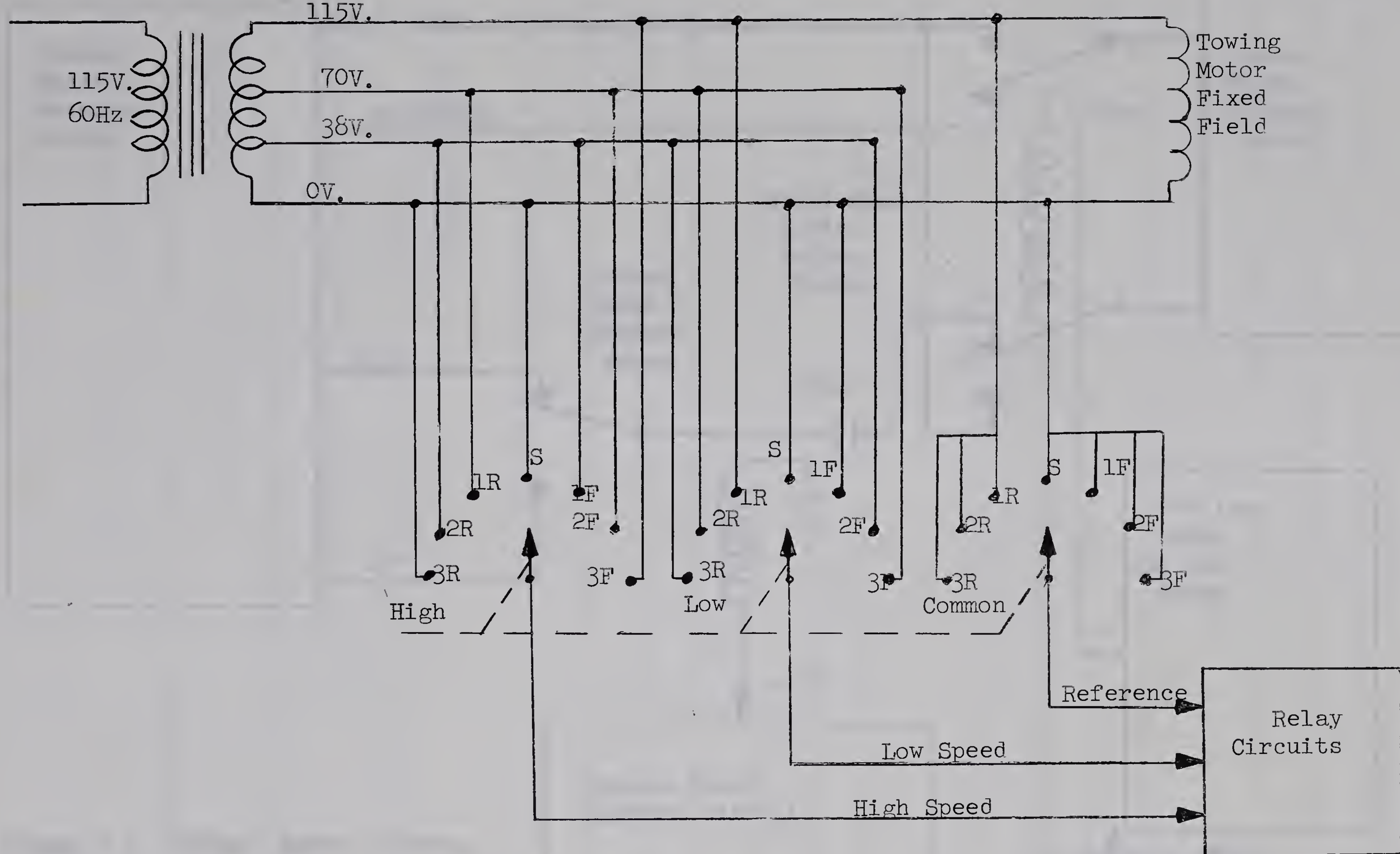

FIGURE 7.4 TOWING SPEED SELECTOR SWITCH SCHEMATIC

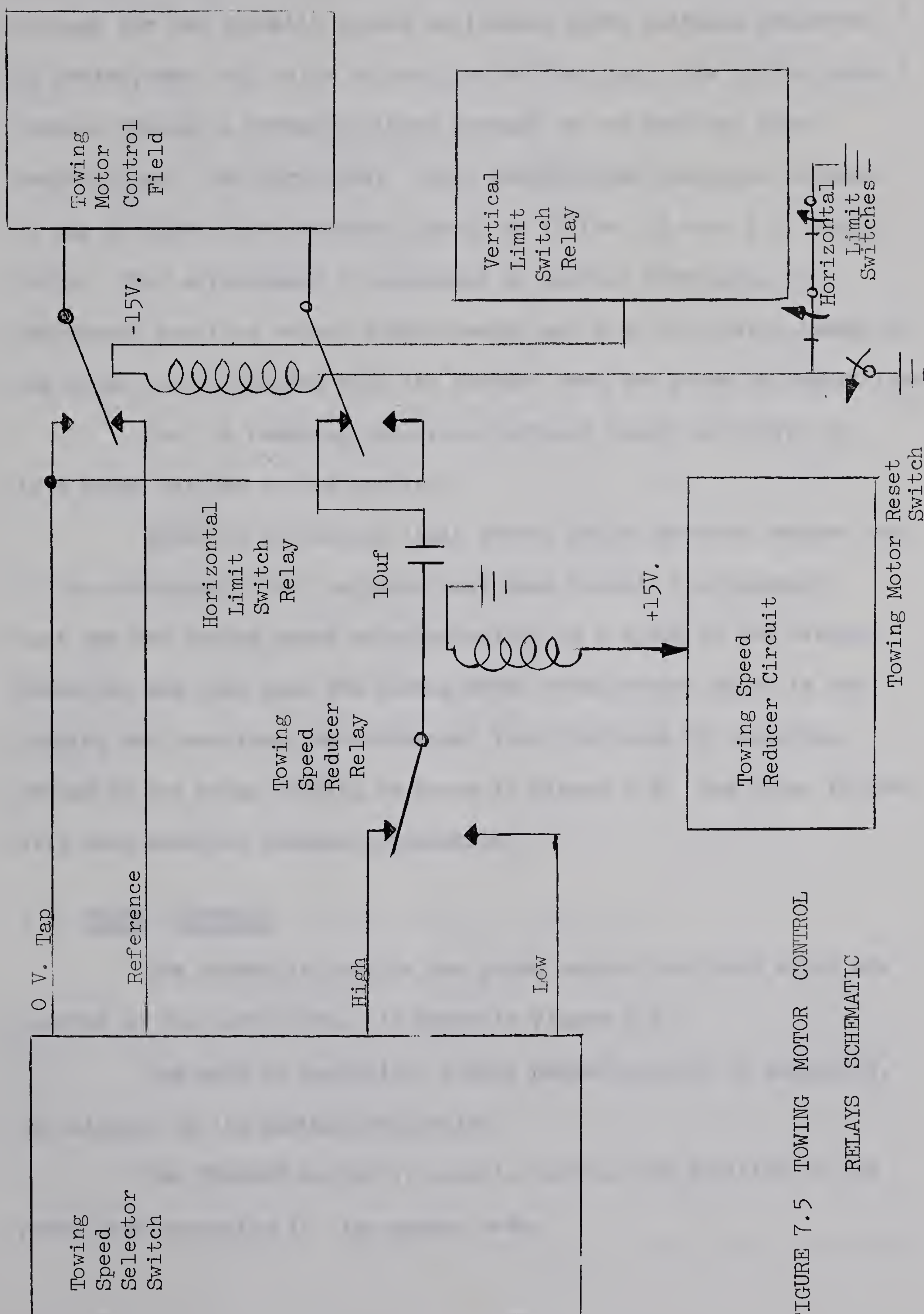

FIGURE 7.5 TOWING MOTOR CONTROL RELAYS SCHEMATIC

The horizontal limit switch relay is normally in the operated position, since ground is supplied to one side of the relay winding through the two normally closed horizontal limit switches connected in series, and -15 volts is supplied to the other side of the relay winding through a normally closed contact on the vertical limit switch relay. The horizontal limit switch relay therefore releases if any of these three contacts opens, or if the -15 volt D.C. supply fails. This arrangement is necessary to prevent overruning the horizontal position output potentiometer and also to prevent damage to the probe due to contact with the surface when the probe is immobilized

due to reaching the probe vertical limits of travel or to a power failure to the trolley.

When the horizontal limit switch relay operates because one of the horizontal limit switches have been opened, the operator must set the towing speed selector switch to a speed in the reverse direction and then push the towing motor reset button which is non-locking and overrides the horizontal limit switches by supplying ground to the relay winding as shown in Figure 7.5. The River Plotter will then continue automatic operation.

7.3 PROBE CONTROLS

The schematic for the two probe control switches which are mounted on the control box is shown in Figure 7.6.

The mode of operation, either manual control or automatic, is selected by the MANUAL-AUTO switch.

The UP-DOWN switch is used to control the position of the probe when operating in the manual mode.

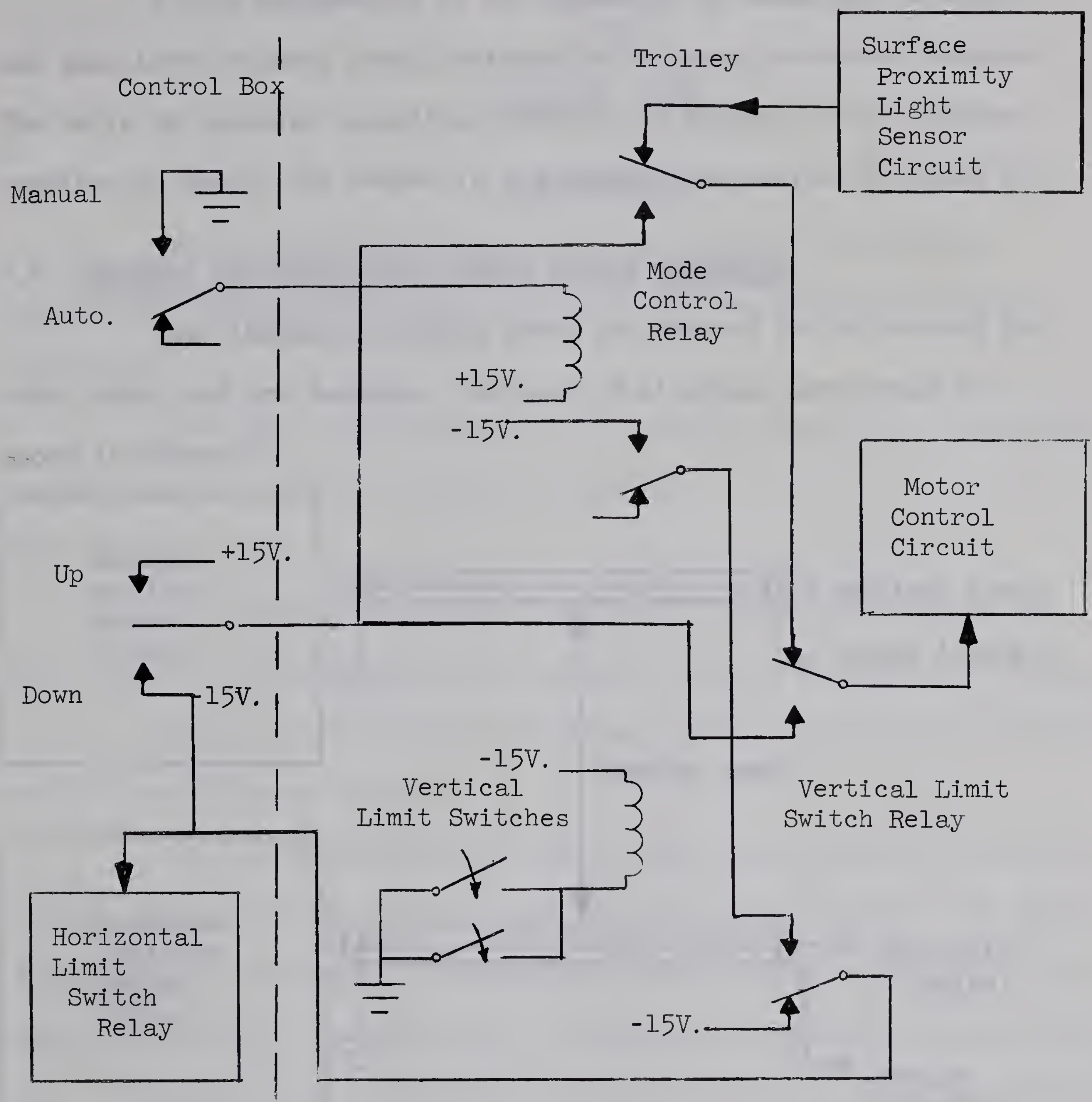

FIGURE 7.6 PROBE CONTROLS SCHEMATIC

Mode Switch		Vertical Limit Switches		Towing Motor		Up - Down Switch		Probe Motor	
Manual	Auto	Open	Closed	Stop	Go	Up	Down	Up	Down
X		X			X	X	X	X	X
X			X		X	X	X	X	X
	X	X			X	X	X		
	X		X	X		X	X	X	

* Assumes neither horizontal limit of travel switch has been reached.

FIGURE 7.7 POSSIBLE FUNCTIONS OF PROBE CONTROL SWITCHES

A full explanation of the operation of these two switches and associated relays, limit switches and circuits is rather tedious. The table of possible operating functions in Figure 7.7 is therefore provided to assist the reader in a detailed examination of Figure 7.6.

7.4 VERTICAL AND HORIZONTAL SIGNAL OUTPUT TERMINALS

Four insulated binding posts are mounted on the control box front panel and are designed Vertical, Horizontal, and Ground as shown in Figure 7.1.

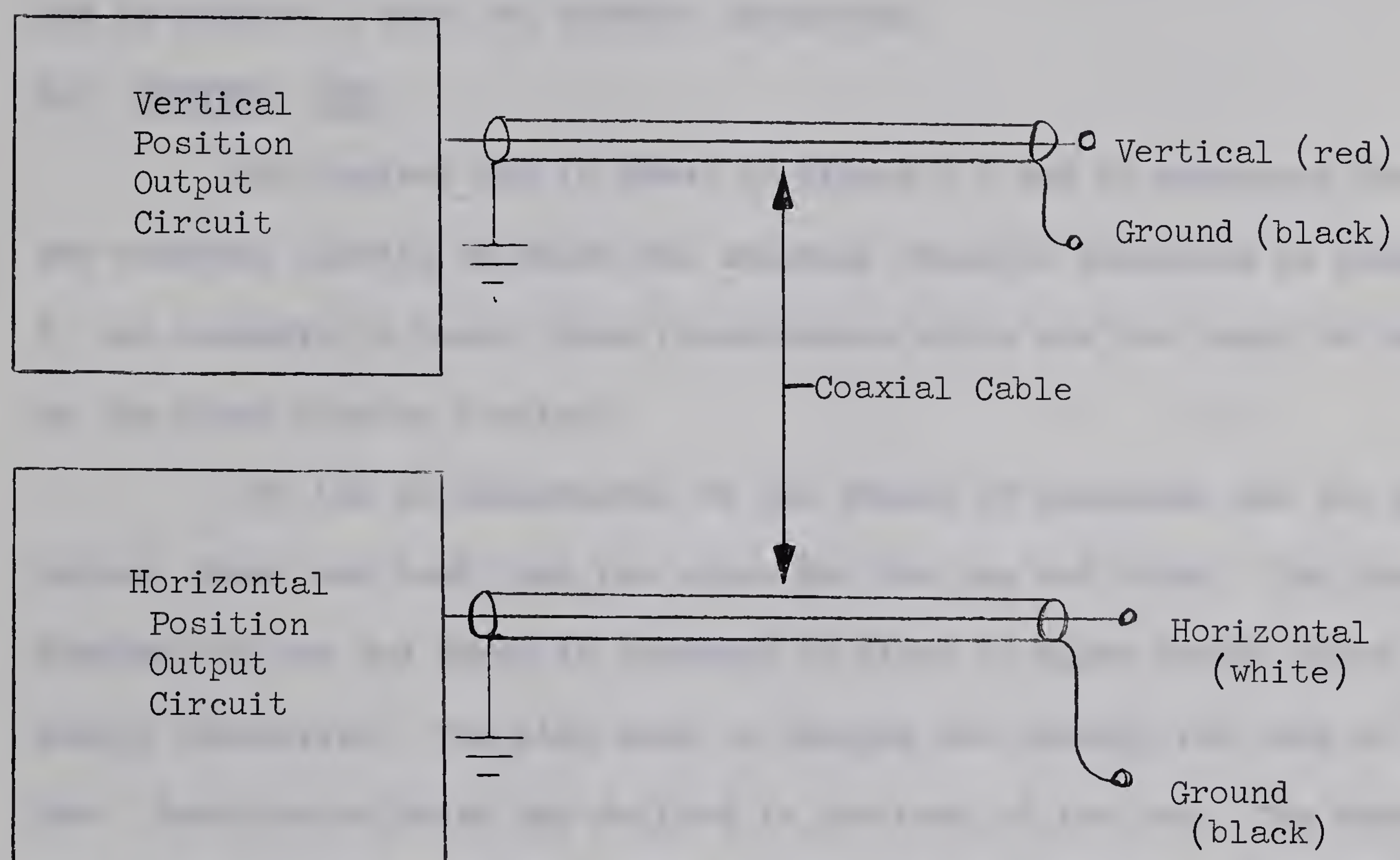

FIGURE 7.8 POSITION OUTPUT SIGNAL SCHEMATIC

The output terminal colors are shown in Figure 7.8. Coaxial cable is used in order to minimize stray pickup from the A.C. power supply leads contained in the same cable which runs from the control box to the trolley.

CHAPTER EIGHT

CONSTRUCTION

The purpose of this chapter is to describe some of the mechanical features of the River Plotter, and the reasons for their selection.

The prime consideration was to satisfy functional requirements and to acheive a neat and orderly appearance.

8.1 CONTROL BOX

The control box is shown in Figure 7.1 and is necessary for two reasons; firstly to mount the external controls described in Chapter 7, and secondly to house three transformers which are too heavy to mount on the River Plotter trolley.

The box is constructed of two sheets of aluminum, one for the bottom, front and back, and the other for the top and sides. The panel forming the top and sides is fastened in place by eight screws which are easily accessible. The line cord is brought out through the back of the box. Ventilation holes are drilled in the back of the box. The front of the box is tilted back slightly and the top overhangs, forming a dust hood.

The control box is twelve inches wide, twelve inches long, six and one half inches high including rubber feet, and weighs 20 pounds.

8.2 TOWING APPARATUS AND CONNECTING CABLES

Figure 1.2 shows the method used to mount the towing motor and gearbox on the rail assembly. The return pulley is mounted at

the opposite end of the rails. The horizontal travel limit switches are mounted on plates which are easily moved back and forth along the rails, and are then clamped in place by wing nuts. The rails have a top face 1/8 inch wide, and are spaced 12.6 inches apart, measuring from center to center. The rails shown were constructed strictly for the testing required in this thesis, and allow a trolley travel of 24 inches.

The main 19 conductor cable runs from the Amphenol connector on the control box front panel to a junction box mounted on the rail assembly by the towing motor. From this junction box, four leads run to the two fields of the towing motor, and one lead runs to the horizontal travel limit switches.

The other fourteen leads are brought out through a connector into a second cable which runs to the connector on the trolley. The cable to the trolley therefore has a connector on each end.

This arrangement is chosen so that if a longer rail system is constructed, it would only be necessary to fabricate a longer cable with connectors at both ends, and no internal connections would need to be disturbed.

In fabricating this cable, small diameter conductors and miniature coaxial cables are used in order that the cables be lightweight, flexible and therefore not cause undue drag on the trolley.

The cable schematic is shown in Figure 8.1.

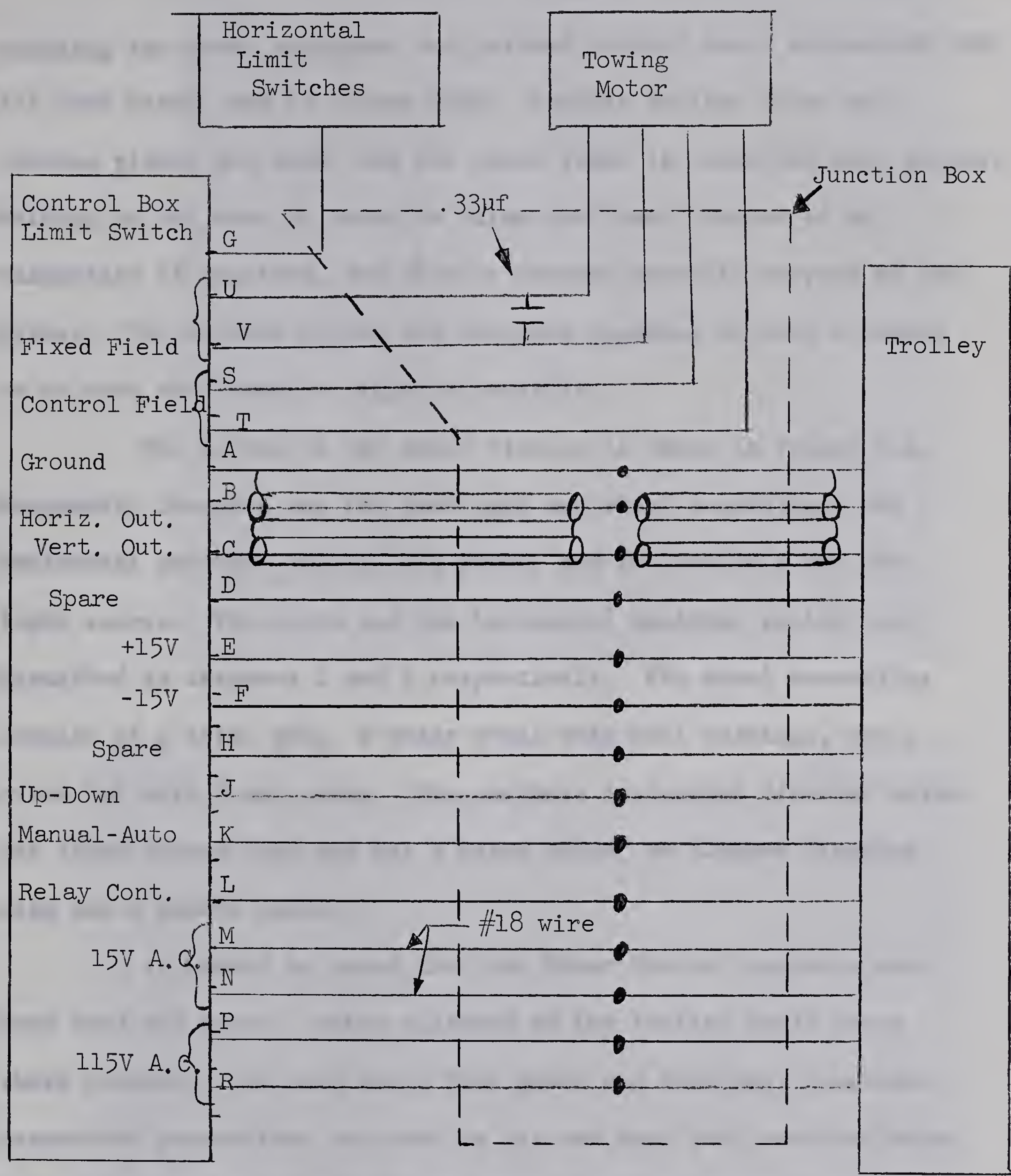

FIGURE 8.1 CONNECTING CABLES SCHEMATIC

8.3 TROLLEY

The frame of the trolley is made from aluminum plate since the trolley must be rigid and as light as possible. The bedplate is 3/8 inch thick, and 12 inches square. The vertical plates for

mounting the probe equipment and printed circuit board connectors are 1/4 inch thick, and 12 inches high. Various smaller brace and spacing plates are used, and the whole frame is assembled with screws. Welding is not used in order to allow the River Plotter to be dismantled if required, and also to prevent possible warping of the plates. The various plates are fastened together in such a manner as to make the frame as rigid as possible.

The bottom of the River Plotter is shown in Figure 8.2. Noteworthy features are the four axle and wheel assemblies, the horizontal position pulley, the probe, and the porthole for the light source. The probe and the horizontal position pulley are described in chapters 2 and 6 respectively. The wheel assemblies consist of a steel axle, a brass wheel with ball bearings, and a nylon hub with a set screw. The porthole is located directly below the light source lamp and has a glass plate, an alumium clamping ring and a rubber gasket.

It should be noted that the River Plotter operates near both sand and water. Water splashed on the trolley could cause short circuits, and sand would foul gears and bearings, therefore reasonable precautions are made to try and keep both sand and water out of the trolley. This is the reason for the porthole cover.

Figure 4.4 shows the front of the River Plotter. The operation of the servo motor, geartrain, leadscrew, probe assembly, and vertical output potentiometer are described in chapter 4. The light source assembly consists of the lamp, an upper and lower plate for holding the lamp, and a three point system for aiming the lamp.

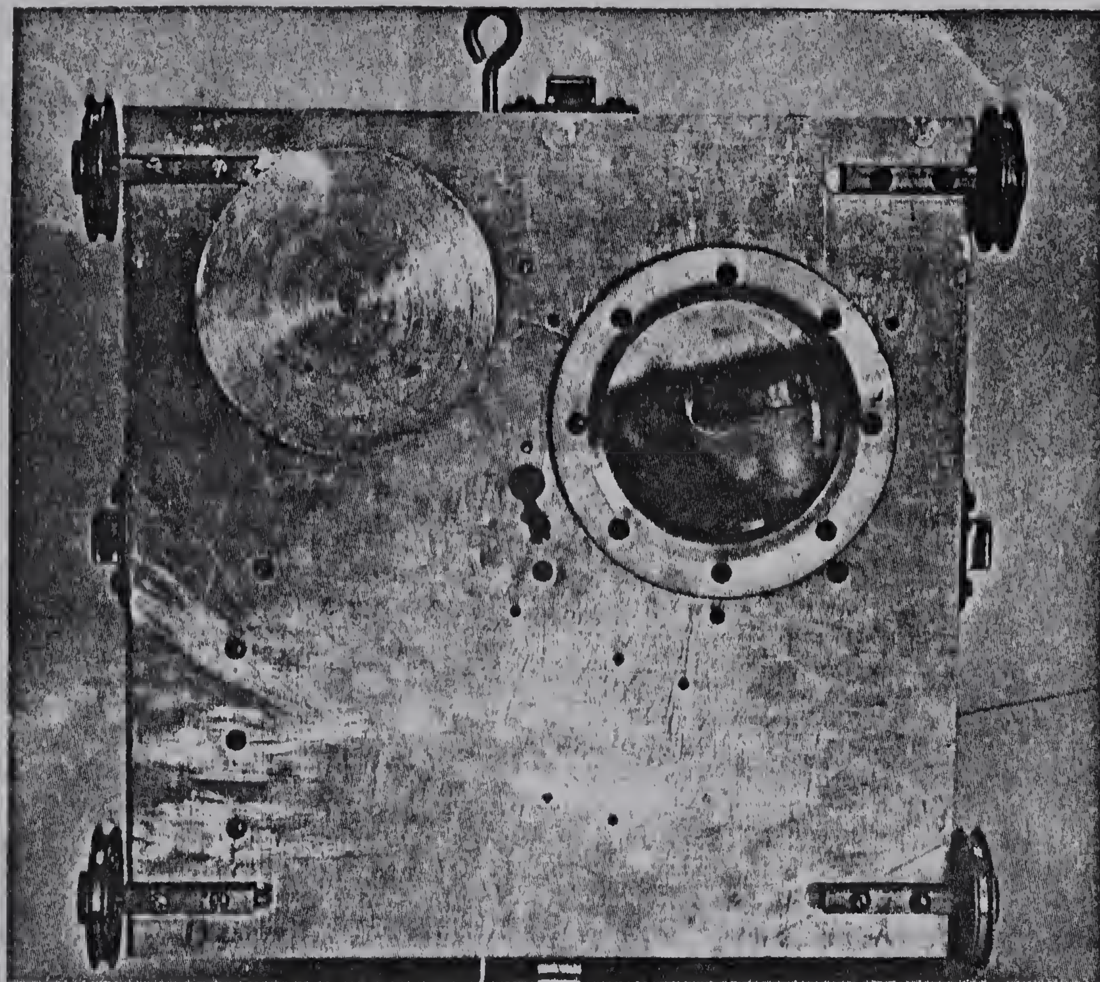

FIGURE 8.2 BOTTOM OF THE RIVER PLOTTER TROLLEY

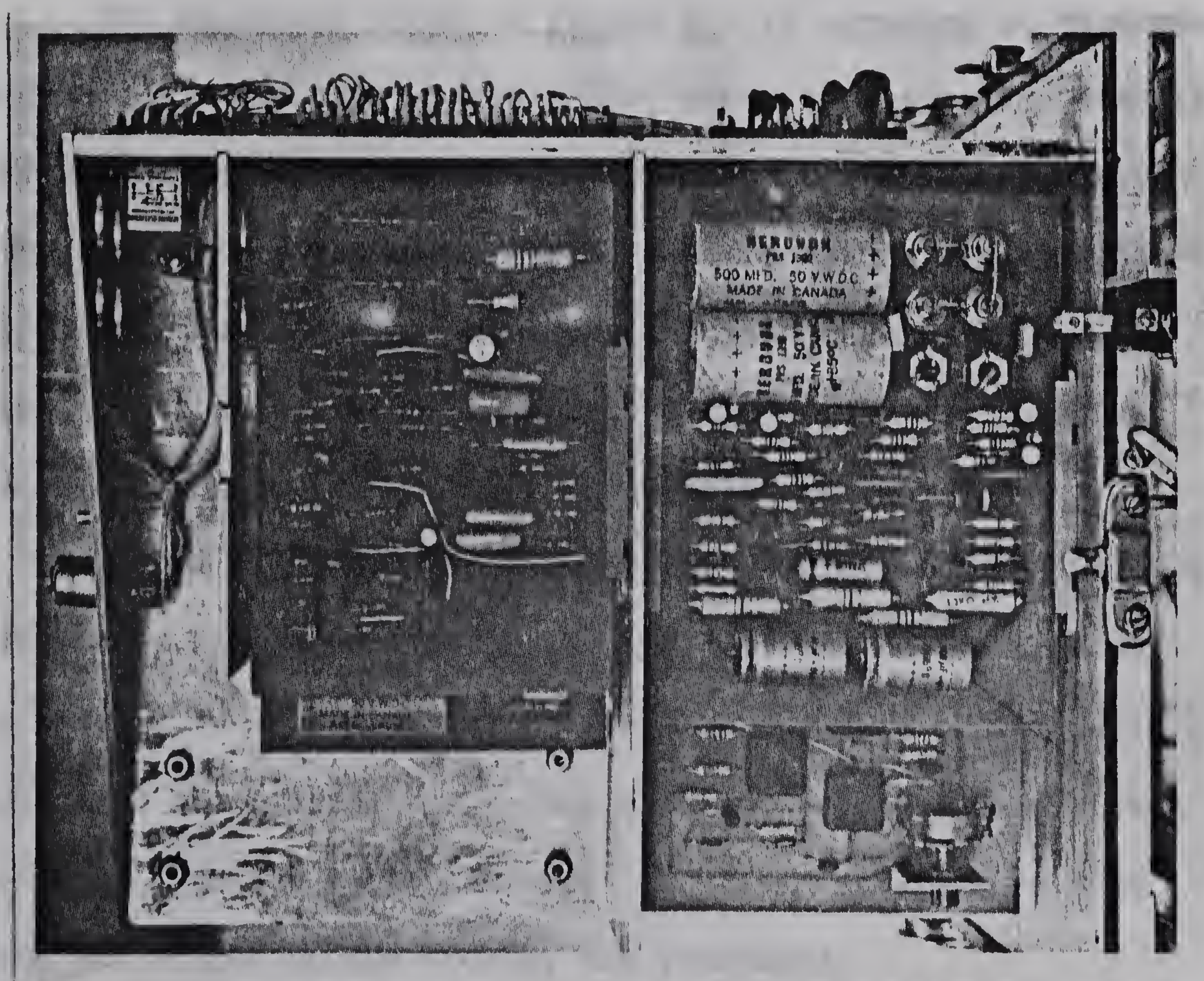

FIGURE 8.3 REAR OF THE RIVER PLOTTER TROLLEY

Above this bracket is the heatsink which mounts the four output transistors for the two power amplifiers, and the phenolic board which mounts the emitter resistors for the power transistors, the two 300 ohm current limiting resistors, the toroid transformers, and the motor capacitors. These components are all part of the servo motor and amplifier circuits. The phenolic board, the heatsink, and the diode bridge bracket are all insulated from the trolley frame to minimize damage from possible short circuits.

The horizontal position potentiometer and gears are mounted on the small plate in the left foreground and are described in chapter 6.

The transformer on the upper right part of the vertical plate is the 115: 36 volt supply for the dual D.C. power supply.

The equipment shown in Figure 1.2 is arranged to be compact and accessible. The lamp, servo motor, power resistors and heatsink all operate above normal indoor air temperature. The heat that results would affect the stability of the transistor circuits on the printed circuit boards, therefore the main vertical plate is designed to act as a divider to make two areas, one for the heat generating components and one for the printed circuit boards.

Figure 8.3 shows the rear of the trolley with the printed circuit boards in place. The printed circuit boards are mounted on the trolley for two reasons; to minimize the size of the cable required from the control box to the trolley, and to reduce pickup on the leads from the light sensors. The disadvantages are that the size and weight of the trolley are increased.

There are five printed circuit boards; the two power amplifiers, the motor control circuit, the miscellaneous circuit board, and the +15, 0, and -15 volt D.C. power supply.

The external cable connector is shown in Figure 8.3 mounted on the top brace plate. The cable from it runs along the top printed circuit board support plate and through a hole in the printed circuit board connector plate. The cable harness on the trolley is designed to be removeable in one piece if required therefore this hole is large enough to pull the bottom part of the connector through.

The small round connector mounted next to the main external connector is for the four leads to the two light sensors in the probe. A connector is used since it is desirable to have the probe easily removeable for periodic servicing and inspection.

To remove the probe, the screws on the lower teflon guide and upper teflon block which fasten the probe to the bedplate and leadscrew are removed, the connector is unpluged and the whole probe assembly is then lifted carefully out.

Figure 8.4 shows the wiring on the printed circuit board connectors. Insulating sleeves are used whenever possible on these connections.

Figure 8.5 shows the River Plotter trolley with the plexiglass cover in place. The cover is used to prevent splashes from fouling the electrical and mechanical components. The trolley has a rubber gasket cemented around the top edge of the bedplate, and when the cover is clamped on with the four overcenter latches, this forms a reasonably water tight joint.

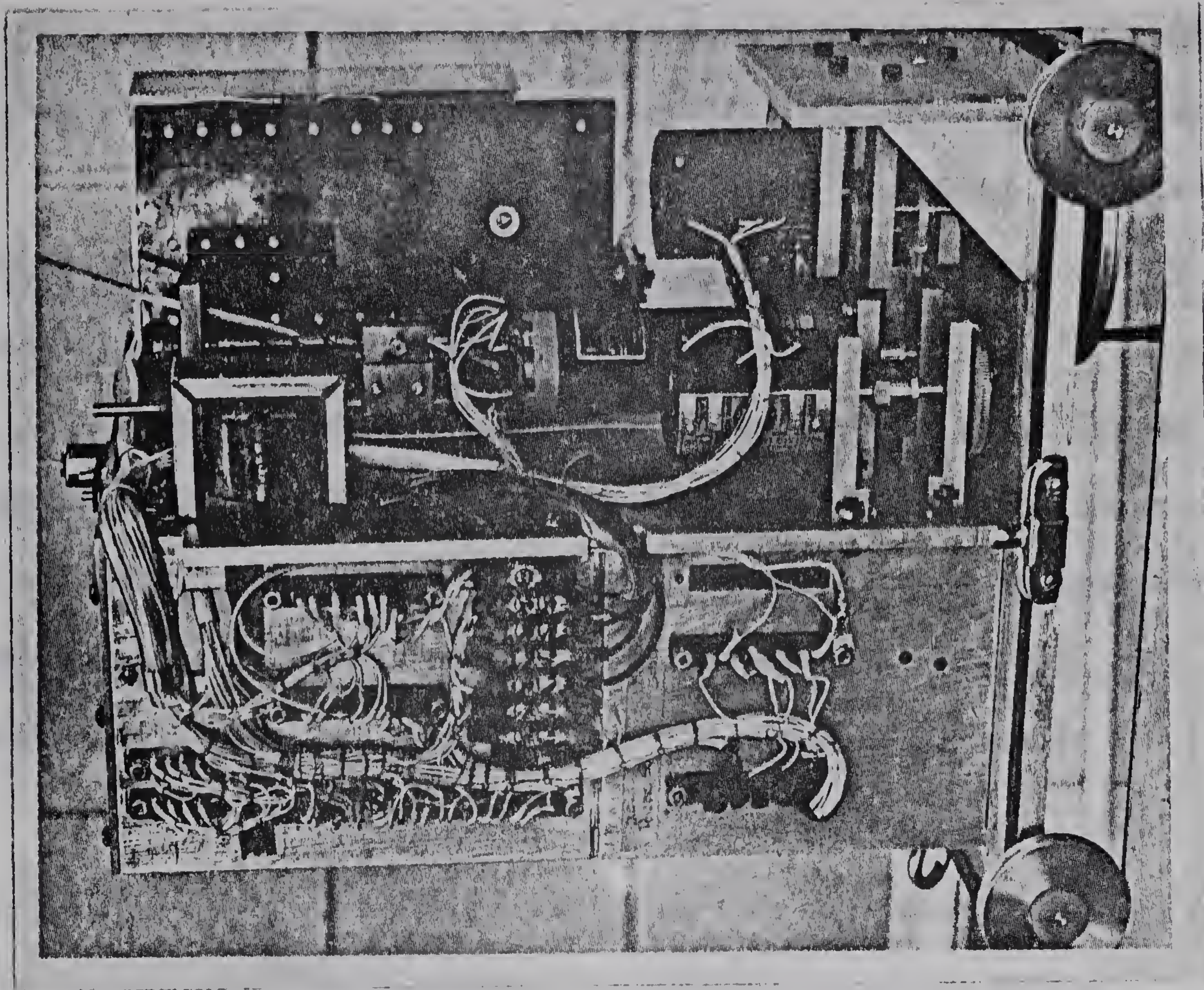

FIGURE 8.4 RIVER PLOTTER WIRING HARNESS

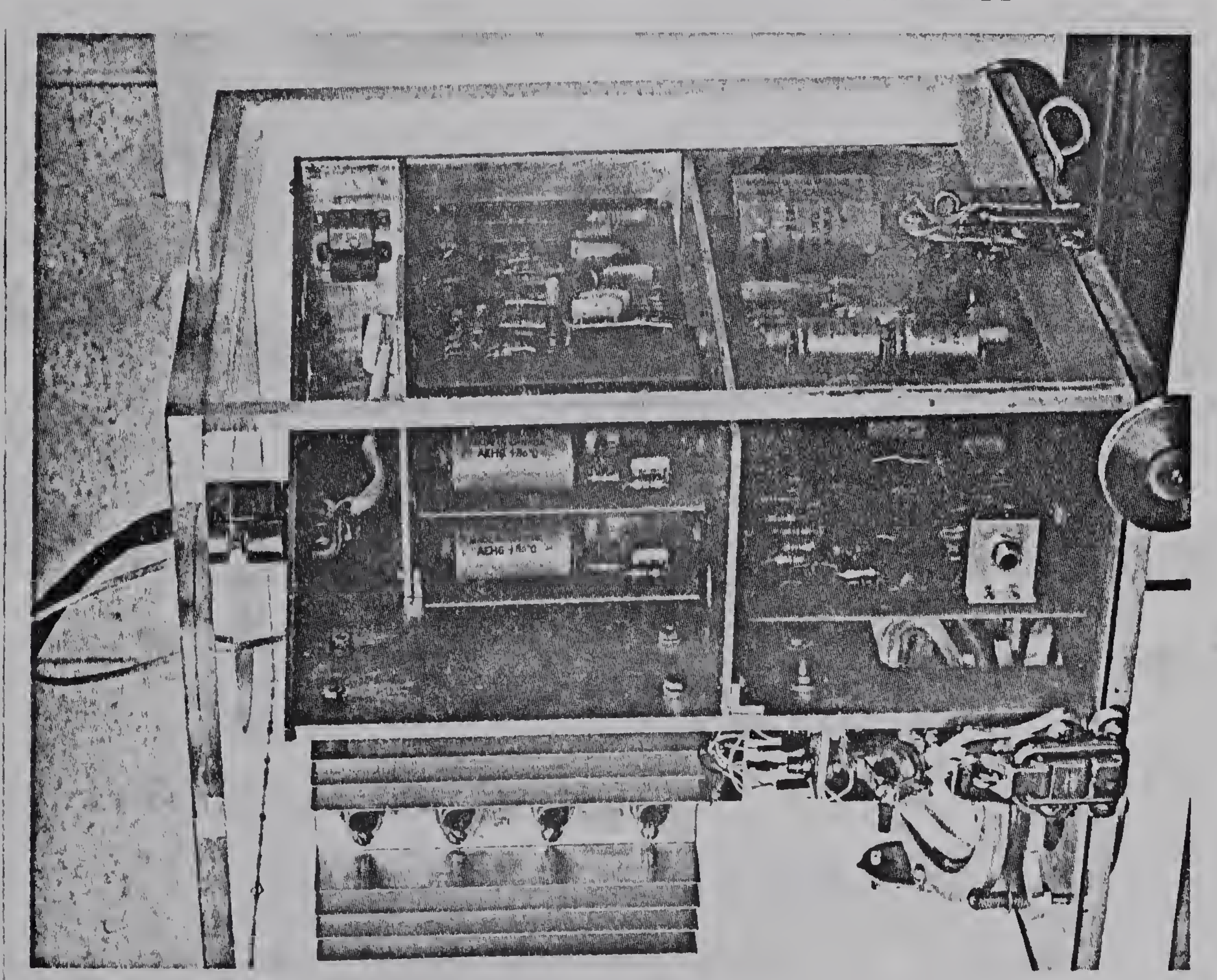

FIGURE 8.5 TROLLEY WITH COVER IN PLACE

A round hole is cut in the top of the box to allow access to the external cable connector, and also to allow heat to escape.

The trolley, with the cover on and excluding the external cable, stands 15 3/4 inches high, is 13 1/4 inches wide, and 15 inches long, including towing eyes.

The weight of the trolley is designed to be as low as practical, since response of the towing motor due to the inertia of the load, the strength of the rail system to prevent excessive deflection, and general ease of handling are all affected. The weight of the trolley with the cover in place is 35 pounds.

CHAPTER NINE

STABILITY

9.1 STABILITY OF THE PROBE POSITIONING SYSTEM

Stability calculations for the River Plotter are of considerable interest since the system must be stable and have minimum overshoot.

The River Plotter is designed to have a damping ratio of about 0.8 to 1.0 in order to avoid overshoot and also to have as broad a bandwidth as practical.

The open loop frequency response, determined by injecting a known signal into the motor control circuit instead of the light sensor signal and then recording the vertical position output, indicates an integrator with a finite gain and a break point at 20 radians/second. This is as expected since the motor and attached load are clearly lowpass. The light sensor gain is easily determined and the tachometer transfer function for low frequencies is that of a differentiator with gain.

If the system is considered to be linear, the closed loop response is readily determined.

The closed loop transfer function is:

$$\frac{C(s)}{R(s)} = \frac{K_1 K_2}{s^2 + (20 + K_2 K_3)s + K_1 K_2}$$

where: K_1 = Probe Gain

K_2 = Positioning Assembly Gain

K_3 = Tachometer Gain

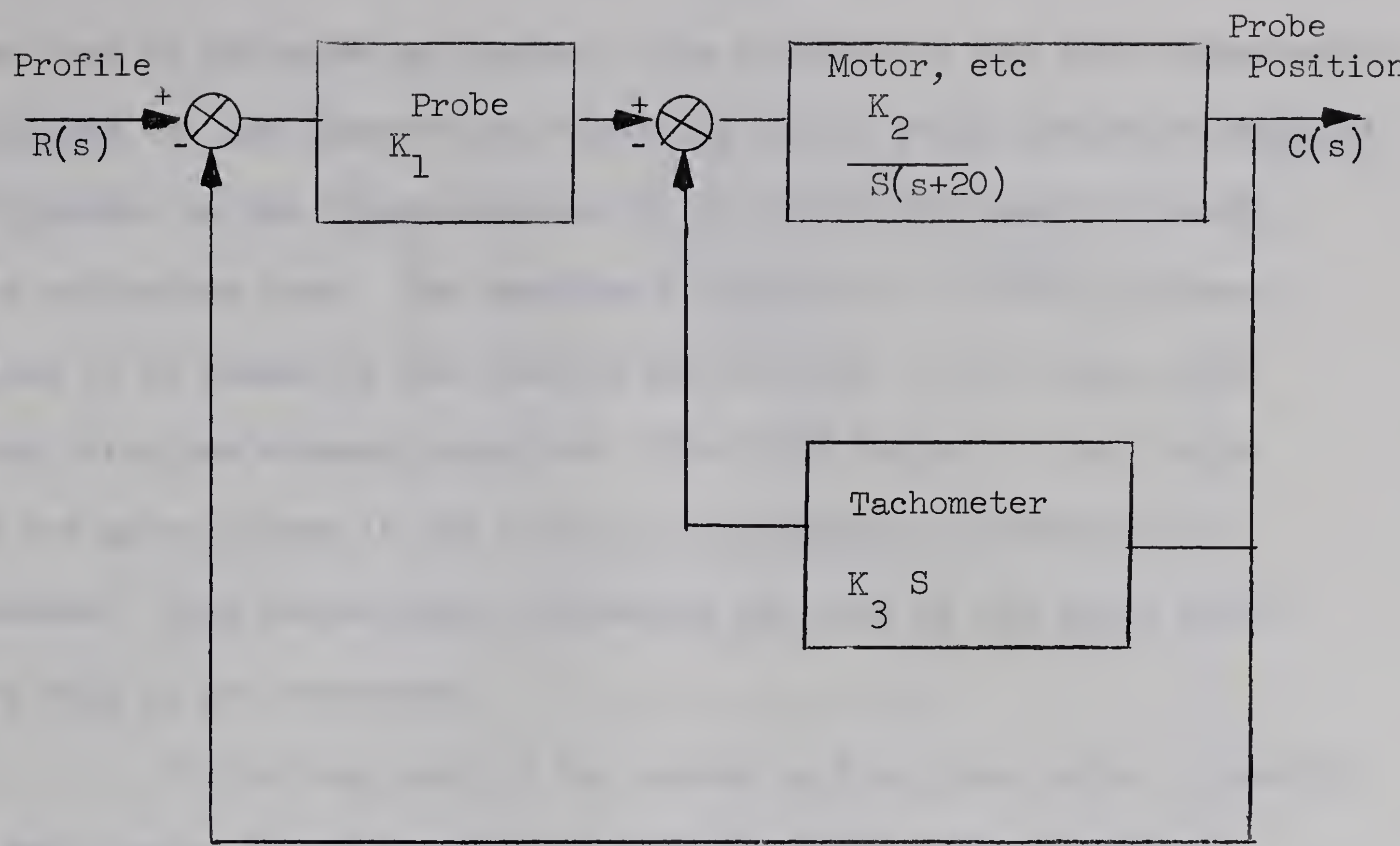

FIGURE 9.1 BLOCK DIAGRAM OF LINEARIZED PROBE POSITIONING SYSTEM

This is a very interesting result, because it indicates that the damping ratio of 0.8 to 1.0 can be achieved by varying the gain K_3 of the tachometer signal, and that the resonant frequency can be controlled by adjusting K_1 and K_2. This is convenient, since K_1 and K_3 are readily adjustable, however, experimental results indicated that the system has definite deadzone and saturation non-linearities. The deadzone is inherent in the motor since the load has friction and the motor cannot overcome it until a certain control voltage is applied. The saturation or limiter characteristic comes primarily from the power amplifiers, since the output voltage amplitude is limited by the bias conditions. The motor control circuit is therefore designed to limit the input to the amplifier to a safe level so that the amplifier can operate at maximum gain and the gain of the motor control circuit

can also be increased as desired. The deadzone is the more undesireable of these two non-linearities, since the system could always be designed to operate on the linear portion of the curve and therefore avoid the saturation zone. The deadzone is difficult to reduce, however, since it is caused by the inertia and friction of the servo motor load which are already minimized. The other factor is the torque of the motor, since if the torque is increased, the deadzone is reduced. This necessitates increasing the size of the servo motor, and this is not convenient.

If the loop gain of the system is high, this acts to amplify a small error signal greatly, so that the error signal required to exceed the deadzone and start the system operating is acceptably small.

There is, of course a practical limit to the loop gain, since too high a gain results in system instability due to noise pickup. This point is determined experimentally and the gain set somewhat below this value.

If the two non-linearities are combined and isolated, the system can be represented as shown in Figure 9.2.

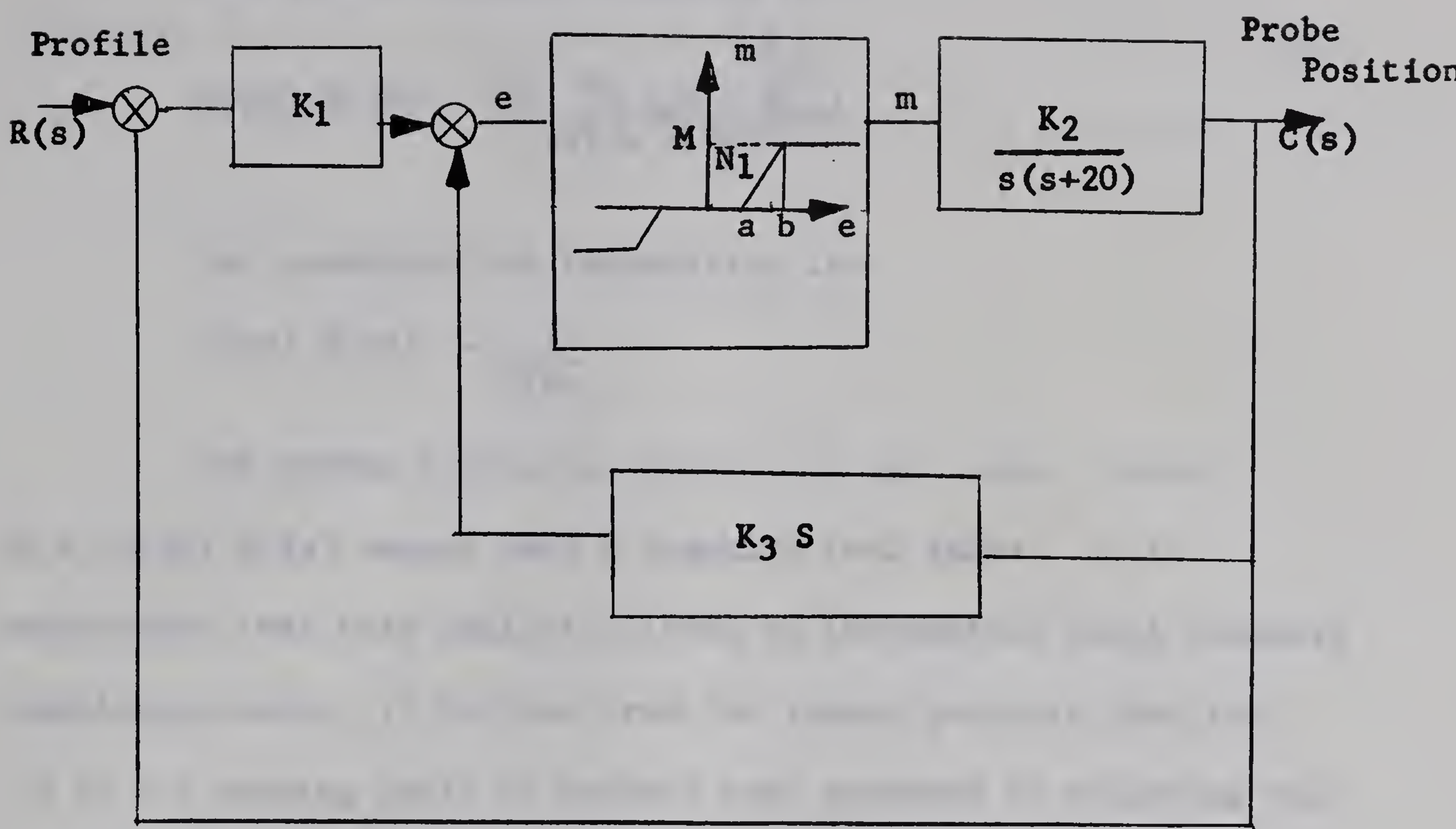

FIGURE 9.2 IDEALIZED NON-LINEAR SYSTEM BLOCK DIAGRAM

Sridhar classifies this non-linearity as type Q (reference 2 page 363), and the describing function for this case is:

$$g(E) = \frac{N_1}{\pi E}\Big[2E(-\theta_1 + \theta_2) + E(\sin 2\theta_1 - \sin 2\theta_2) + 4a(\cos\theta_2 - \cos\theta_1)\Big] + \frac{4M}{\pi E}\cos\theta_2$$

$$b(E) = 0\ ,$$

where $e = E\sin\theta$,

$$\sin\theta_1 = \frac{a}{E}\ ,$$

$$\sin\theta_2 = \frac{b}{E}\ .$$

The equivalent non-linear gain, $K_{eq} = g(E) + jb(E)$, therefore, since measurements show that $b = 4a$, and $N_1 = 1$, $-\frac{1}{K_{eq}}$ exists on the negative real axis between -1.23 and $-\infty$.

The linear transfer function is;

$$G(jw)\ H(jw) = \frac{K_1 \quad K_2 \left(jw + \frac{K_3}{K_2}\right)}{jw(jw + 20)}$$

The condition for instability is:

$$G(jw)\ H(jw) = \frac{-1}{Keq}$$

The system is stable, since, for any real value of w, G(jw) H(jw) cannot have a negative real value. It is unfortunate that this analysis yields no information about relative stability, however, it follows from the linear analysis that the .8 to 1.0 damping ratio is probaly best achieved by adjusting the tachometer gain.

Experimental results show that under certain conditions, the system oscillates, indicating that the system previously considered is oversimplified. The instability occurs when the probe is operating near the lower limit of travel and a visual inspection reveals that the backlash in the geartrain and leadscrew is primarily responsible. Other factors are the tuning of the servo motor, the level of the surface illumination, and the tolerances in the lower probe support.

The backlash was not considered in the previous non-linear analysis since it was thought to have been minimized and not appreciable compared to the deadzone.

The three combined non-linearities are approximately of class E (reference 2 , page 359), and the describing function expressions for this case are formidable.

Redesign of the lower support, further fitting of the leadscrew assembly, retuning the servo motor, and a slightly higher level of surface illumination relieved the problem and system stability is satisfactory.

CHAPTER TEN

PERFORMANCE

10.1 FREQUENCY RESPONSE

The River Plotter will track a sinusoidally varying surface which changes 0.3 inches in depth from minimum to maximum up to and including 4.5 Hz. Above 4.5 Hz, phase lag increases rapidly, and the error becomes excessive.

The frequency response was measured using a 4 inch diameter drum which was coated with sand. The drum was mounted 0.15 inches off-center, and driven by a variable speed motor.

The vertical output from the River Plotter was observed to determine amplitude and frequency, and contacts on the drum were used to determine phase relationships.

10.2 PROFILE MEASURING TESTS

Sample profiles were measured at various speeds in both towing directions. The River Plotter tracks slightly below the operating point on an upward slope, and slightly above the operating point on a downward slope. The tracking error is proportional to the rate of surface change, which is a combination of towing speed and the actual slope of the surface. The operating point remains at a known distance above a consistent surface, so that a method of minimizing error is to plot a profile by running the River Plotter in both directions and averaging the two curves and applying corrections according to a calibration curve. Results within ± 1/32 inch are obtainable using this method when the towing speed is selected to avoid large discrepancies in the plot.

Figure 10.1 is a set of sample profiles of the bottom for clear water and a white sand bottom. Curves A, B, and C were run at towing speeds 1, 2 and 3 respectively in both directions of trolley travel. The large discrepancy at the right hand end of the plot is due to the probe tip re-entering the water . This type of error is unavoidable in the plot, but with experience in interpreting the plots, this should not prove to be a serious problem, and in fact, water surface level can be determined from this plot.

Profile A in Figure 10.2 was plotted for essentially the same profile as in Figure 10.1, but with ink added to the water to make it murky. The bottom in the deepest part was just visible with room lighting. At the right hand end, the River Plotter would not track on the downward slope in shallow water, and had to be restarted by remote control.

Profiles B, C, and D in Figure 10.2 are of a wet white sand surface and were recorded at towing speeds 1, 2 and 3 respectively in both directions of trolley travel. At the right hand end of curve B, the upper line was run at speed 2 to show the effect of towing speed when operating on a steep slope.

No sample profiles were taken of water surfaces, however earlier trials of the experimental River Plotter showed this was feasible. The only change required to plot water surfaces is that appropriate biasing resistors would have to be selected for the light sensors.

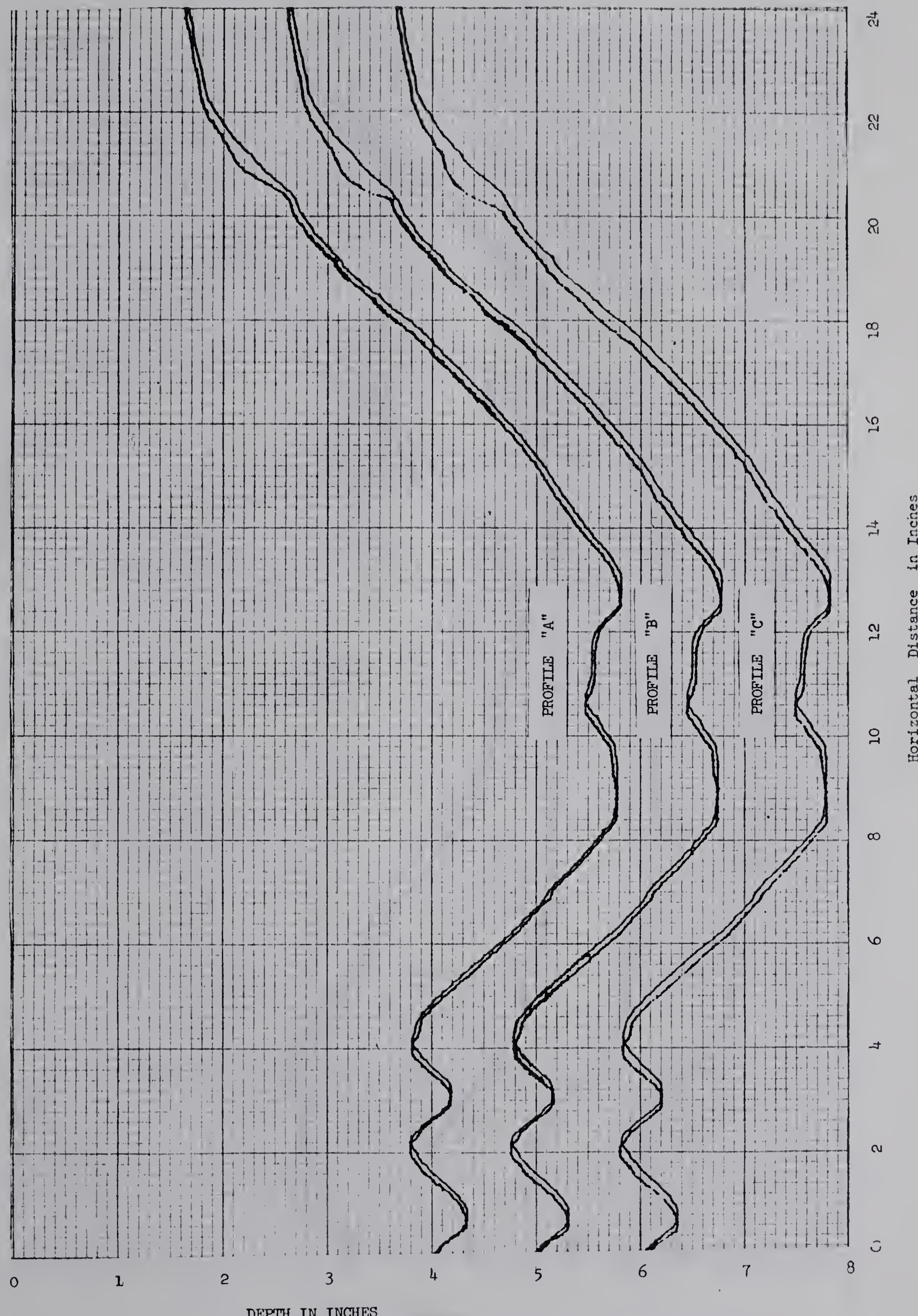

FIGURE 10.1 SAMPLE PROFILES

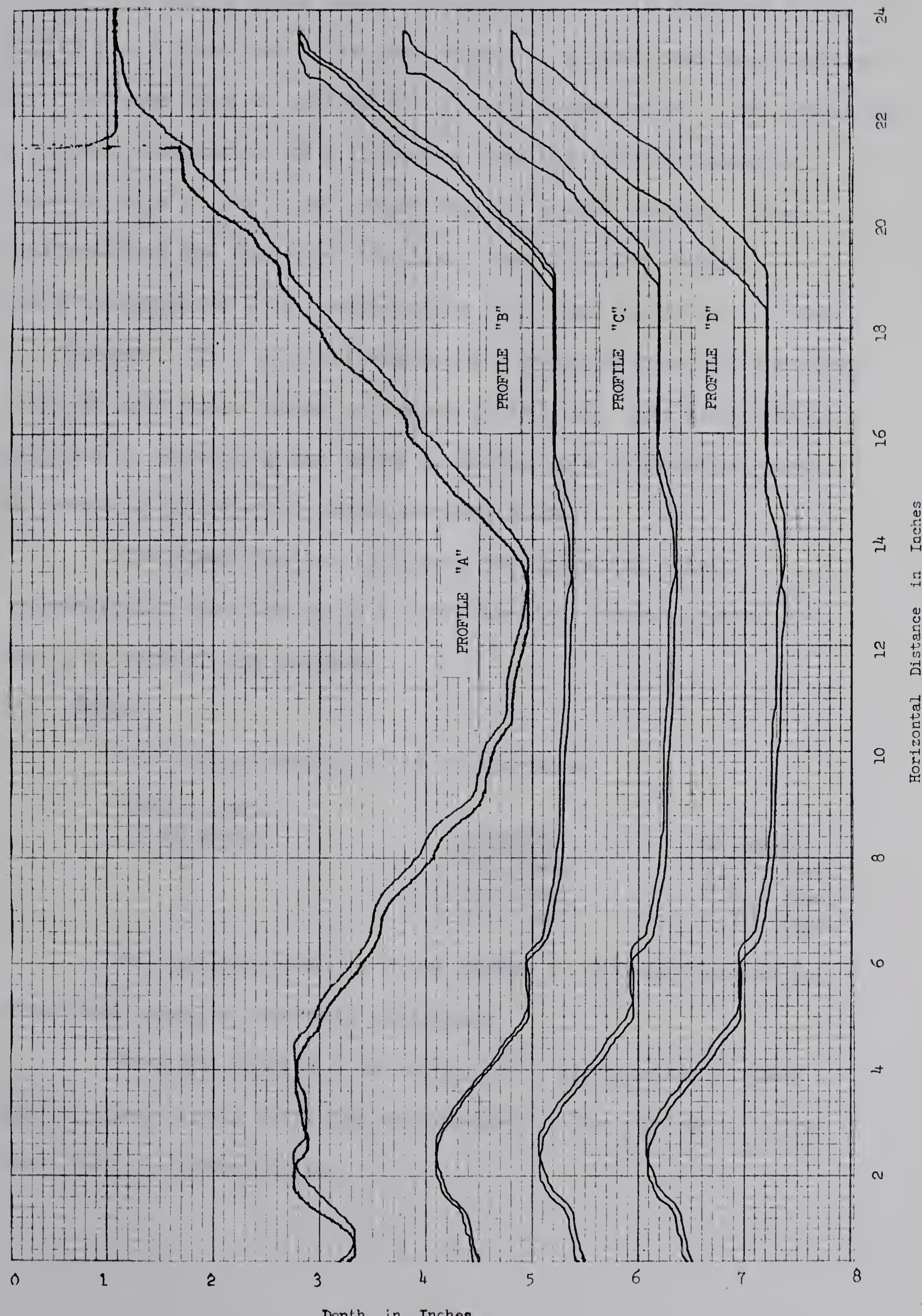

FIGURE 10.2 SAMPLE PROFILES

10.3 PROBE POSITION CHARACTERISTICS

A sample probe position characteristic is shown in Figure 2.1(b) for a level wet white sand surface. A curve was also measured for the same type of surface but on a 30 degree slope. The operating point was measured to be 0.16 inches from the bottom, measuring from the edge of the light sensor nearest to the surface. The distance from the center of the light sensor to the surface would therefore be 0.19 inches, since the light sensor is 1/8 inch in diameter. This is a difference of 0.06 inches from the operating point of 0.13 inches shown in Figure 2.1(b), but this error can be overcome by correcting the curve according to a calibration curve of operating point error versus surface slope.

The River Plotter will seek the operating point automatically once the probe is positioned by remote control to within an inch of the surface.

10.4 Speeds

The towing speeds of the trolley are:

TOWING SPEED SELECTED	FORWARD	REVERSE
1	0.9in./sec.	1.1in./sec.
2	1.3in./sec.	1.4in./sec.
3	1.7in./sec.	1.7in./sec.

The maximum speed of probe travel is 3 inches/second in either the upward or downward direction.

From the profile B in Figure 10.2, the maximum surface rate of change for a plot with discrepancy on the plot of $\pm$ 1/32 inch is 0.4 inches/second.

CONCLUSIONS

The instrument described in this thesis measures the bottom profiles of river models with an accuracy of $\pm$ 1/32 of an inch at traversing speeds up to 1.7 inches/second. The instrument can be remotely controlled and operates automatically. The probe is small in cross-section, and operated properly, does not cause turbulence or scouring. Only 115 volt, 60 Hz. power is required for operation.

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